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MECHANICAL PROPERTIES OF WROUGHT TUNGSTEN

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AF MATERIALS LABORATORY
RESEARCH AND TECHNOLOGY DIVISION
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

Project No. 7381, Task No. 738103

(Prepared under Contract No. AF 33(616)-7385 by
The Hughes Tool Co.—Aircraft Division, Culver City, Calif.
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FOREWORD

This report was prepared by the Hughes Tool Company - Aircraft Division, Culver City, Calif., under USAF Contract No. AF 33(616)-7385. This contract was initiated under Project No. 7381, "Materials Application," Task No. 738103, "Data Collection and Correlation".

The work was administered under the direction of the Directorate of Materials and Processes. Deputy for Technology, Aeronautical Systems Division. Mr. C. L. Harmsworth was the project engineer.

This report covers work conducted from June 1960 to December 1961.

ABSTRACT

The mechanical properties and quality of commercially available tungsten sheet was investigated. For the initial quality control phase, hardness, microstructure, chemical impurities, flexural properties and tensile strength were determined on material from three sources. Based on these test results a specification requiring high quality material with high cold reduction was formulated.

For the second phase of testing three powder lots of tungsten sheet, per the specification, were procured from five sources. The tensile test results on this material are presented for room temperature, 1000°, 2000°, 3600° and 4400°F. Good correlation between room temperature hardness and tensile strength was found. The material from one producer consistently displayed a limited amount of plastic elongation at room temperature.

A third phase was conducted to obtain detailed design data on three lots of material obtained from one producer. This data is reported on separately as Volume II of this report.

This technical documentary report has been reviewed and is approved.

D. A. Shinn, Chief
Materials Information Branch
Materials Application Division
AF Materials Laboratory

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PART I

TEST EQUIPMENT

All tensile tests were performed on the HTC-AD Elevated Temperature Test Machine shown in Figure 1. This machine has a load capacity of 50,000 pounds and is capable of performing tension, compression, creep, and axial fatigue tests at elevated temperatures. It employs a closed loop servo system that allows load, load rate, strain, or strain rate to be programmed and automatically held constant. Test specimens heating is accomplished by direct electrical resistance. Power source capacity for heating is 10 kilowatts.

Load is measured with a 5000-pound Cox and Stevens load cell through a Kintel Model 114A amplifier and Moseley Model 3S recorder. The accuracy of the system is within plus or minus one percent or plus or minus 2 pounds whichever is greater.

The water-cooled extensometer is shown in Figure 2. Spring-loaded ceramic points grip the specimen in the test section. The ceramic has been selected so as to insulate the linkage arms electrically and thermally and to retain satisfactory hardness at very high temperatures. The gage length is 2.0 inches.

The strain transducer used is a one-inch travel Markite DC potentiometer with a linearity of 0.1 percent of full scale. Strain is recorded through a Kintel Model 114A amplifier and Moseley Model 3S recorder. The one-inch travel was chosen so that the strain rate would be controlled and held constant for test material with up to 50 percent elongation in the two-inch gage length.

Below 1800°F, temperature is measured with .005 diameter Chromel-Alumel thermocouples and Leeds and Northrup Speed-O-Max H recorders. From 2000° to 3700°F, temperature is measured with an automatic two color pyrometer, the Shawmeter Model SMPI. Above 3700°F, temperature is measured with a similar Shawmeter model SMP3. The calibration of a Leeds and Northrup brightness pyrometer model number 8622 was checked against a calibrated wide filament tungsten lamp (General Electric tube T-24) up to a brightness temperature of 3500°F.

The calibration agreed consistently within the maximum difference of 18°F at 3500° which is considered within the reading error of the L & N pyrometer. The Shawmeter calibration was then checked against the L & N pyrometer and the calibrated lamp. The data reprinted in DMIC Report 127, "Physical and Mechanical Properties of Tungsten and Tungsten Base Alloys" has been used as the relation between color, brightness and true temperature

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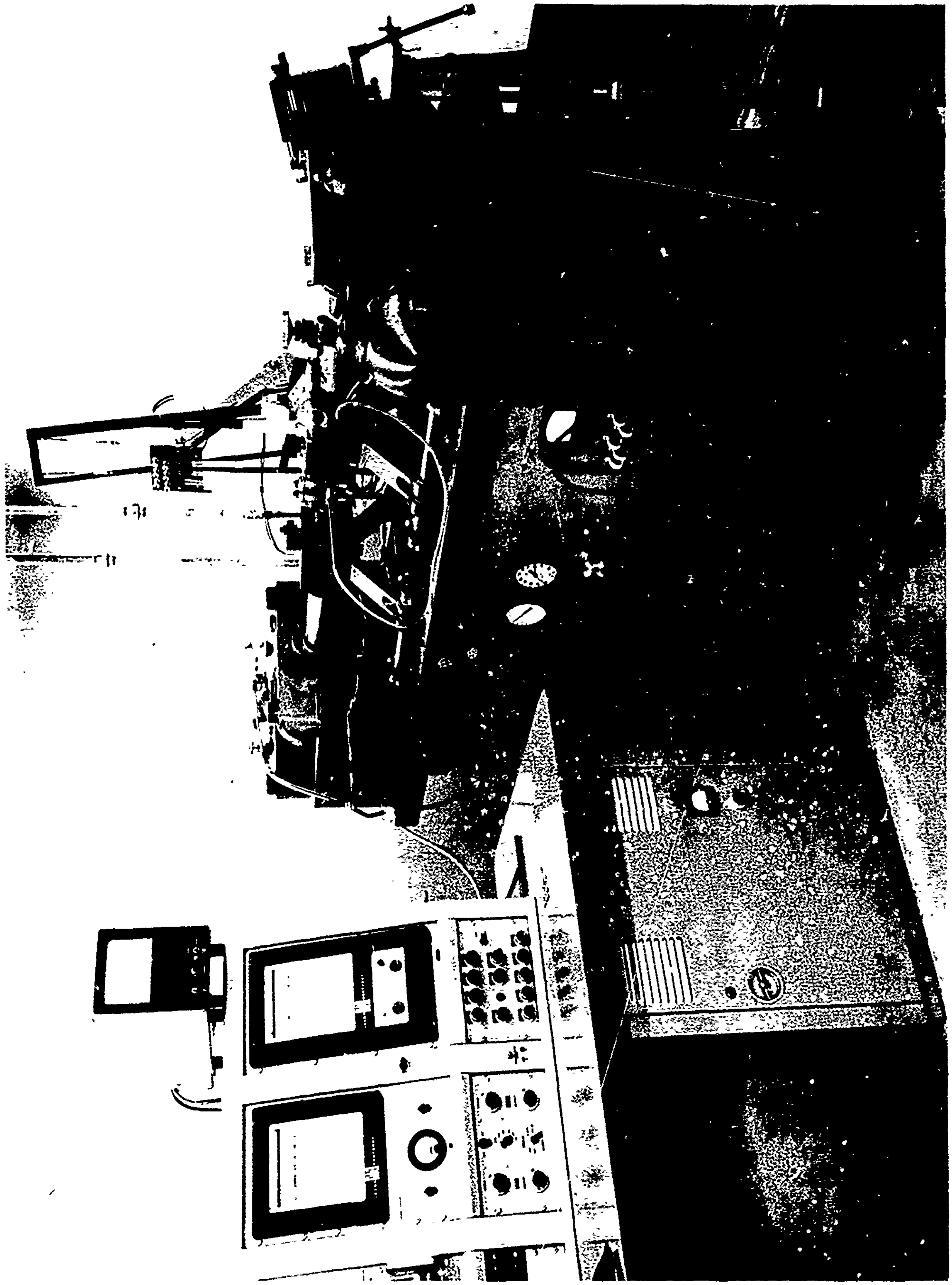


Figure 1. Elevated Temperature Test Machine

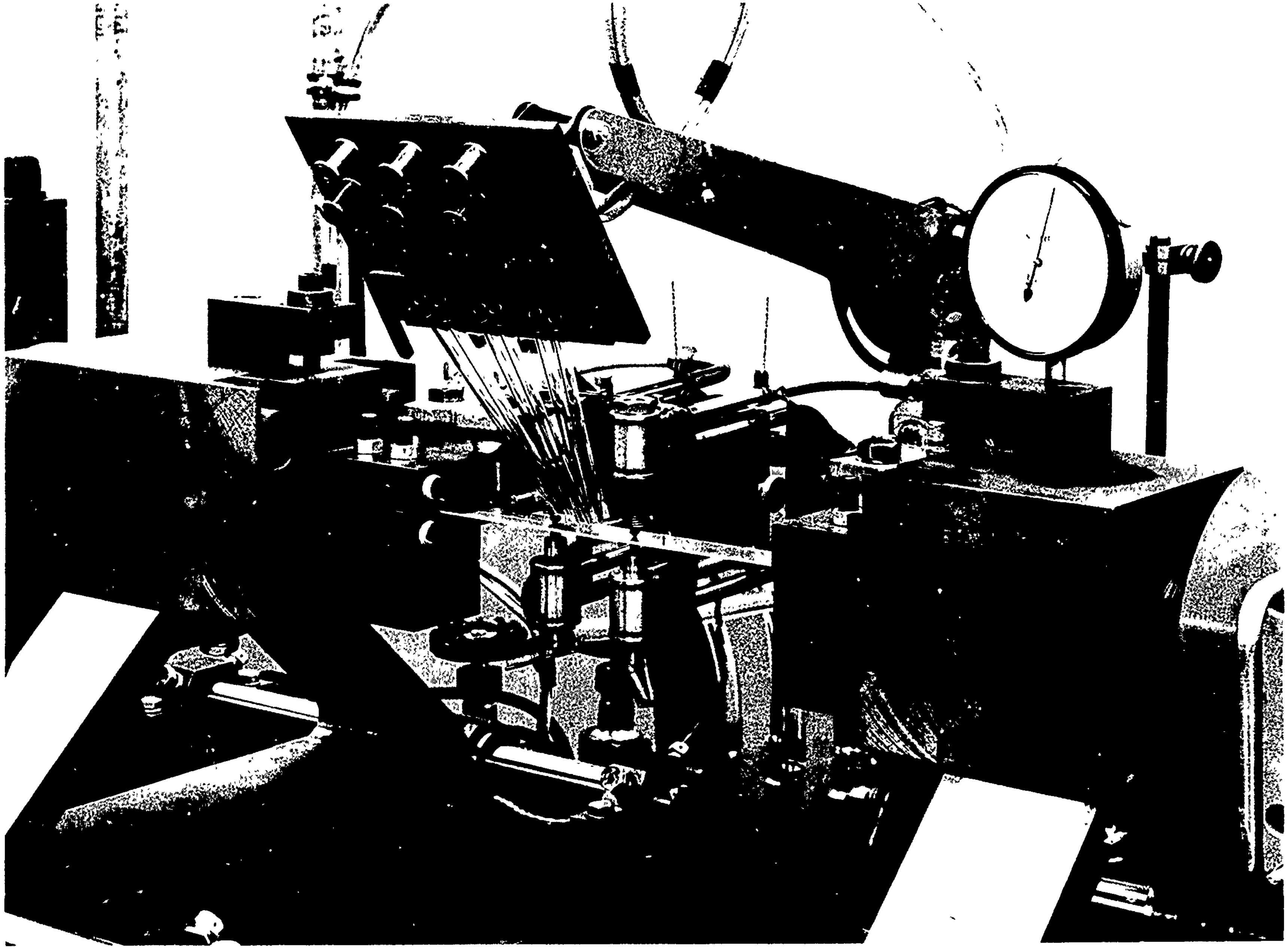


Figure 2. Water Cooled Extensometer

for tungsten. Some calibration error was found in Shawmeter SMPI and corrected. The L & N pyrometer and the Shawmeter Model SMPI with the corrected calibration and Shawmeter model SMP3 were then compared under the black body conditions of the HTC-AD 5100°F carbon resistance furnace and found to be in agreement within the reading error of the L & N pyrometer. Regular calibration checks of the Shawmeters have been conducted as calibration changes of up to 3 percent over time periods of several months have been found.

Atmospheric protection is provided with a very small argon flushing chamber as shown in Figures 3 and 4. Specimens protected by this system show no visible oxidation.

Gripping of tensile specimens is accomplished by the use of friction clamps. Pinholes are not required in the test specimens. The stress concentration factor in the specimen at the edge of the grips is of low magnitude to prevent failure of the room temperature brittle tungsten at the grips.

BEND TESTS

The bend test jig for determination of bend transition temperature is shown in Figure 5. The test specimens were .050" x .500" x 1.7".

Heating was accomplished with lamps, and 28 gauge iron-constantan thermocouples were used to measure temperature. An Emery-Baldwin Tate 5000-pound capacity testing machine was used for load application and measurement.

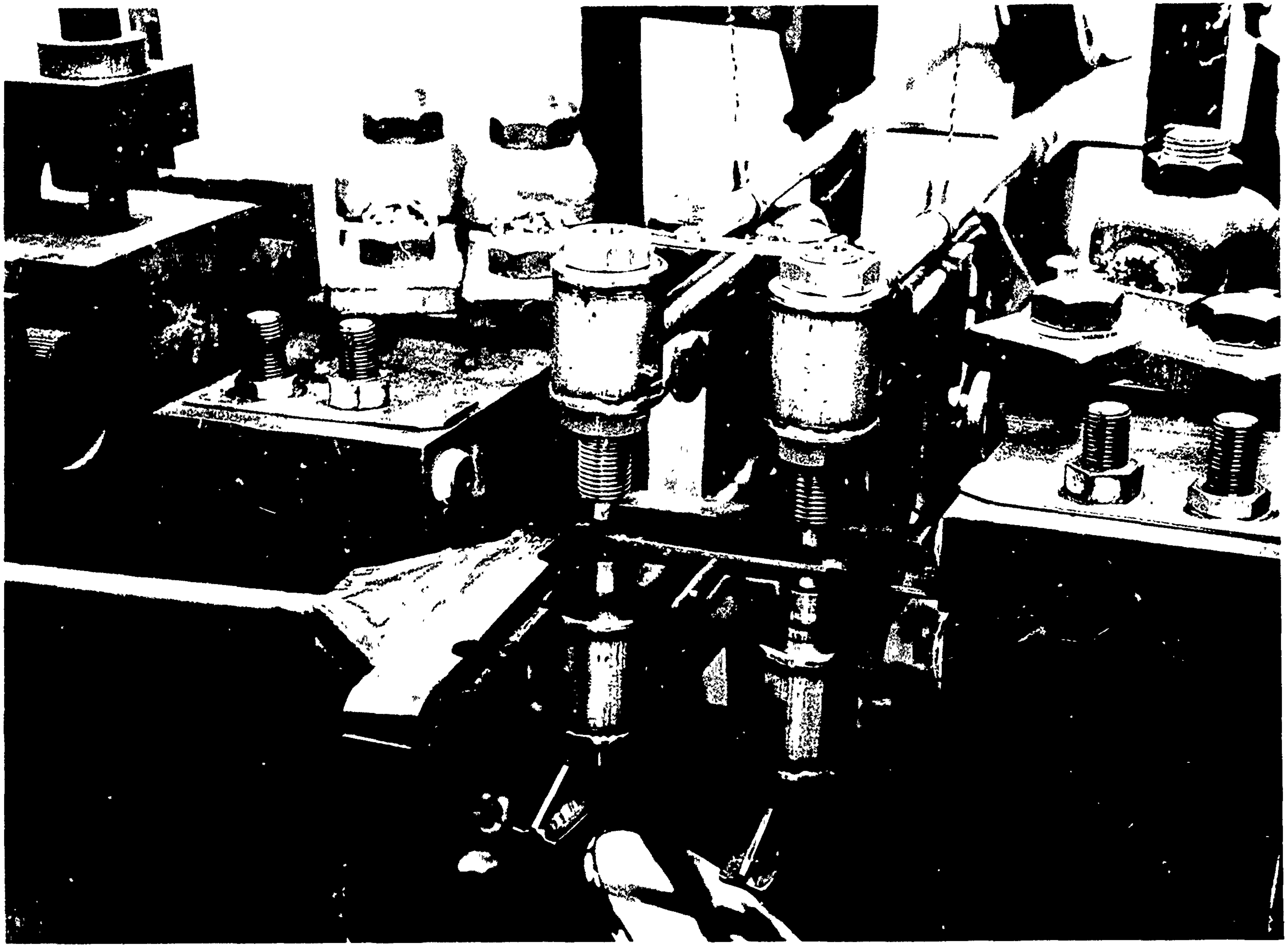


Figure 3. Inert Gas Flushing Chamber in Open Position

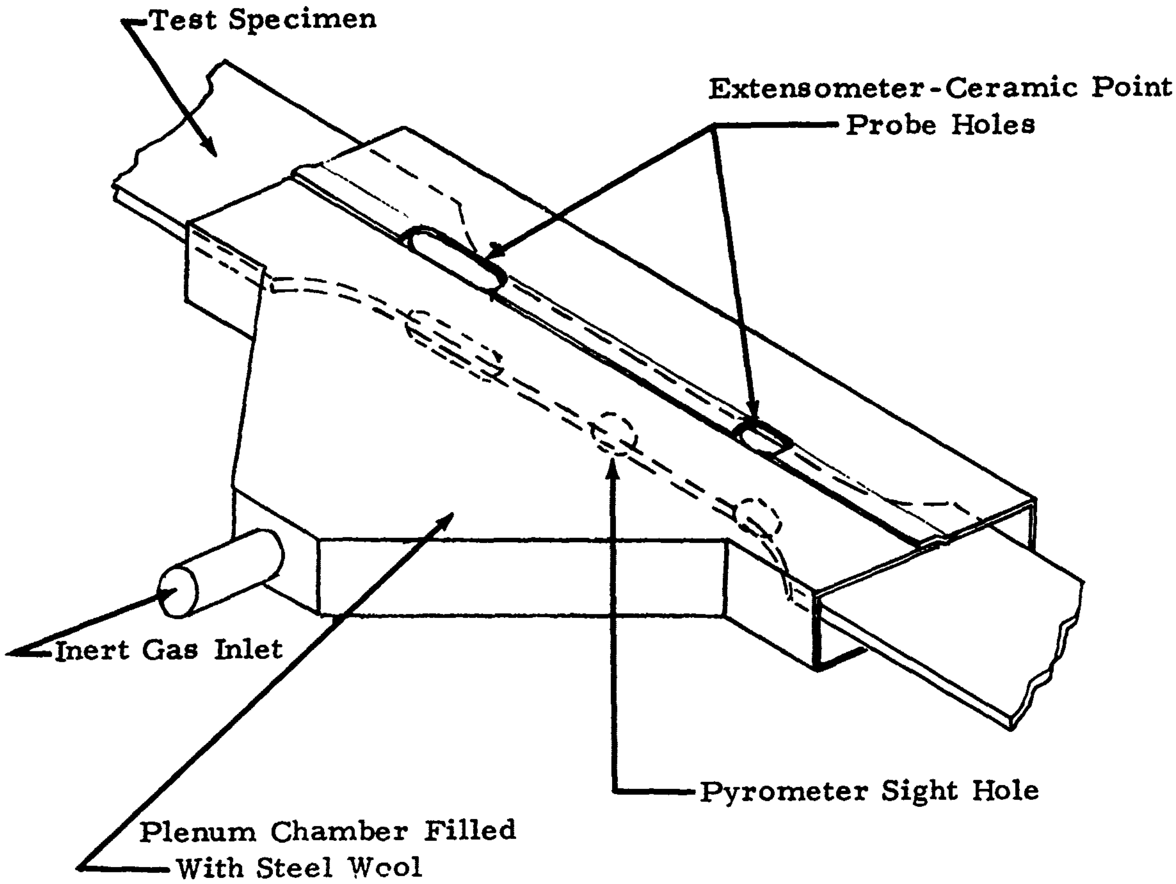


Figure 4. Inert Gas Flushing Chamber Schematic

Figure 5. Bend Test Jig

PART II

DETERMINATION OF THE QUALITY OF TUNGSTEN PROCURED FROM THREE SOURCES

INTRODUCTION

The four principal refractory metals -- columbium, molybdenum, tantalum, and tungsten -- are being considered for aerospace vehicle components where service temperatures exceed the melting temperatures of the nickel - and cobalt-base high temperature alloys. Tungsten has the highest melting temperature of any metal in economical supply and offers the best properties at the highest temperatures.

Because of the rapidity with which the use of wrought tungsten has grown, the necessary property determinations important for efficient application of the material have not received adequate attention. The purpose of this program is to determine the mechanical properties of commercially pure tungsten between room temperature and 5000°F.

Commercially pure tungsten sheet in the recrystallized condition has a ductile-brittle transition temperature above approximately 400°F. By subjecting the tungsten to sufficiently large rolling reductions below the recrystallization temperature, it will display room temperature ductility accompanied by a large increase in tensile strength. This effect is commonly observed in commercially pure drawn tungsten wire. However, high purity single crystals of tungsten have a tensile transition temperature below -96°F as shown by Atkinson[1]. The material tested in this phase did not display any room temperature ductility.

As no material specification less general than "commercially pure tungsten" was available, the first phase of this program was the establishment of a material specification that would insure a high quality level. Cold pressed and sintered metal in three lots from each of three producers were ordered in the following conditions: (1) sheet, low cold reduction and stress relieved, (2) sheet, low cold reduction as rolled, (3) sheet, high cold reduction and stress relieved and (4) bar-stress relieved. Two tensile tests of each type were run at room temperature, 2000°F, and at 3600°F. In addition, bend transition temperature tests were run on the sheet material. This test information, plus data derived from metallography and chemical analysis formed the basis for a material specification.

[1] Atkinson et al in WADD Technical Report 60-37.

Meetings were held with representatives of the three producers chosen to supply material for the quality control phase of this program. The material needs and purposes of the program were presented. The requirements for producer process reporting as shown in Table I were adopted and accompanied each material order. The material requested for this phase is shown in Table II.

All the information received from the producers concerning the test material is shown in Tables III, IV, and V.

The thickness, flatness, surface defects and internal defects for this material is shown in Tables VI, VII, and VIII. A photograph of a tungsten sheet which had a comparatively high degree of warpage is shown in Figure 6.

The test specimen coding description for this material is shown in Table IX.

A major degree of sheet cracking prior to testing occurred with the Producer B material but not with the Producer A or C materials. A total of five out of fifteen of the Producer B tungsten sheets fractured during handling and fabrication into test specimens.

TABLE I

REQUESTED PROCESSING DATA

The complete processing and fabrication history of each of the lots of material was requested so that lots with similar property values could be reproduced at a later date. The following information was requested for each piece of material:

1. Chemistry - basic and trace elements when starting to make the ingot.

2. Method of ingot consideration.

3. Rolling conditions - cold, warm (hot-cold), or hot, with the limits defined as follows:

   a. Cold-room temperature to 800°F
   b. Warm - 800°F to the recrystallization temperature
   c. Hot - above the recrystallization temperature

4. Percent thickness reduction after last recrystallization anneal.

5. Last process heat treatment before final pass.

6. Final temper condition - e.g., stress-relieved, full annealed, as rolled, etc.

7. Method of final surface treatment - e.g., chemical mechanical, etc.

8. Definition of surface finish - e.g., shiny, matted, etc.

9. Extent of "doping", if any. The material used and amount (high, medium, or low).

10. Final density.

11. Material to be properly identified.

TABLE II

TUNGSTEN ORDERED FROM EACH PRODUCER FOR QUALITY CONTROL EVALUATION

All material ordered cold pressed and hydrogen sintered.

I. Sheet - - A representative low cold reduction (30 percent suggested) - stress relieved.

Lot A - 0.050 x 7 x 11-1/2 (long grain)

Lot B - 0.050 x 7 x 11-1/2 (long grain)

Lot C - 0.050 x 7 x 11-1/2 (long grain)

II. Sheet - - A representative low cold reduction identical to I except without stress relief.

Lot A - 0.050 x 7 x 11-1/2 (long grain)

Lot B - 0.050 x 7 x 11-1/2 (long grain)

Lot C - 0.050 x 7 x 11-1/2 (long grain)

III. Sheet - - A representative high cold reduction, (60 percent suggested) - stress relieved.

Lot A - 0.050 x 7 x 11-1/2 (long grain)

Lot B - 0.050 x 7 x 11-1/2 (long grain)

Lot C - 0.050 x 7 x 11-1/2 (long grain)

IV. Bar - - Forged (not rolled) - stress relieved

Lot A - 0.250 x 1-1/8 x 11-1/2

Lot B - 0.250 x 1-1/8 x 11-1/2

Lot C - 0.250 x 1-1/8 x 11-1/2

TABLE III

PRODUCER A REPLIES TO TABLE I PROCESS REPORT

1. CHEMISTRY POWDER LOT ANALYSIS

	LOT A	LOT B	LOT C
Fe	0.0042 to .0036%	Less than 0.01%	Less than 0.01%
Ni	none	none	none
CaO	none	none	none
O_2	0.28%	0.02 %	0.04%
C	less than .01%	less than .01%	less than .01%
Distillation Residue	0.02%	0.01%	0.01%
Grain Size	4.38 microns	4.17 microns	3.68 microns

2. CONDITION

Rolled

3. ROLLING CONDITIONS

Low cold reduction sheet - 80% reduction above recrystallization temperature and 20% below

High cold reduction sheet - 50% reduction above recrystallization temperature and 50% below

4. THICKNESS REDUCTION (%) AFTER FINAL RECRYSTALLIZATION ANNEAL

Low reduction sheet about 80%

High reduction sheet about 50%

TABLE III (continued)

5. LAST PROCESS HEAT TREATMENT BEFORE FINAL PASS

See Item No. 3

6. FINAL TEMPER CONDITION

Sheet No.	Cold Reduction	Stress Relief
A I A	20%	2 min. at 1000°C
A II A	20%	none
A III A	50%	2 min. at 1000°C
A I B	20%	900-1100°C
A II B	20%	none
A III B	50%	900-1100°C
A I C	20%	900-1100°C
A II C	20%	none
A III C	50%	900-1100°C
A IV A	Forged Bar	Temp. not received
A IV B	Forged Bar	1400-1500°C
A IV C	Forged Bar	1400-1500°C

7. FINAL SURFACE TREATMENT - chemical

8. SURFACE FINISH - etched

9. DOPING - low

10. DENSITY - 100% of theoretical

TABLE IV

PRODUCER B REPLIES TO TABLE I PROCESS REPORT

1. Chemistry

A. Powder

No analysis available

B. Ingot

	LOT A	LOT B	LOT C
Carbon	0.018	0.018	0.018
Oxygen	0.003	0.003	0.003
Nitrogen	0.001	0.001	0.001
Iron	0.001	0.005	0.005
Calcium	0.004	0.004	0.005
Nickel	---	0.003	0.003
Molybdenum	0.010	0.030	0.020
Silicon	0.010	0.010	0.010
Columbium	---	---	0.001

2. Consolidation

All ingots were resistance sintered in an atmosphere of dissociated ammonia.

3. Rolling conditions

Rolling was carried out entirely between 2200°F and 2900°F

TABLE IV (continued)

4. Reduction after last recrystallization anneal

Sheet No.	Condition
B IV A	0.250" Stress Relieved
B IV B	0.250" Stress Relieved
B IV C	0.250" Stress Relieved
B II A	30% Reduction-as Rolled
B I A	30% Reduction-Stress Relieved
B II B	30% Reduction-as Rolled
B I B	30% Reduction-Stress Relieved
B II C	30% Reduction as Rolled
B I C	30% Reduction-Stress Relieved
B V A	90% Reduction-Stress Relieved
B V A	90% Reduction-Stress Relieved
B III A	60% Reduction-Stress Relieved
B III B	60% Reduction-Stress Relieved
B III C	60% Reduction-Stress Relieved

5. Process Heat Treatment Before Final Pass
   2275°F except for 30% reduction pieces which were heated to 2820°F.

6. Final Temper Condition
   See Item 4. Stress relieving at 2475°F for 20 minutes

7. Final Surface Treatment
   Acid etching in a nitric, sulfuric, hydrochloric, and hydrofluoric acid solution.

8. Surface Finish
   Matte

9. Final Density 100% of theoretical

10. Doping information not supplied.

TABLE V

PRODUCER C REPLIES TO TABLE I PROCESS REPORT

1. Spectrographic and chemical analysis of tungsten powder

All analyses in percent by weight - ND= not detected

Element	Lot A	Lot B	Lot C
Na	.001	<.001	<.001
K	.003	.001	.002
Al	<.001	<.001	<.001
Ca	<.001	<.001	<.001
Si	<.001	<.001	.002
Mo	.001	.002	.001
Fe	<.001	<.001	<.001
Cr	<.001	<.001	<.001
Ni	<.001	<.001	<.001
Cu	<.001	<.001	<.001
Mn	<.001	<.001	<.001
Mg	<.001	<.001	<.001
Sn	<.001	<.001	<.001
Co	ND	ND	ND
Ag	ND	ND	ND
Pb	ND	ND	ND
Th	ND	ND	ND
Zr	ND	ND	ND
O_2	.017	.025	.015
C	--	.002	.001

2. Cold pressed from powder and consolidated by direct sintering. Details considered proprietary.

3. Final condition

Sheet No.	Powder Lot	% Cold Reduction	Stress Relief
C I A a	A	67	1650°F, 45 min.
C I A b	A	67	1650°F, 45 min.
C I B a	B	67	1650°F, 45 min.
C I B b	B	67	1650°F, 45 min.
C I C a	C	67	1650°F, 45 min.

TABLE V (continued)

Sheet No.	Powder Lot	% Cold Reduction	Stress Relief
C I C b	C	67	1650°F, 45 min.
C II A a	A	67	none
C II A b	A	67	none
C II B a	B	67	none
C II B b	B	67	none
C II C a	C	67	none
C II C b	C	67	none
C III A a	A	80	1650°, 45 min.
C III A b	A	80	1650°, 45 min.
C III B a	B	80	1650°, 45 min.
C III B b	B	80	1650°, 45 min.
C III C a	C	80	1650°, 45 min.
C III C b	C	80	1650°, 45 min.
C IV A a	A	-	none
C IV A b	A	-	none
C IV A c	A	-	none
C IV B a	B	-	none
C IV B b	B	-	none
C IV B c	B	-	none
C IV C a	C	-	none
C IV B b	C	-	none
C IV C c	C	-	none

4. Surface has a matte finish resulting from caustic and acid cleaning.

5. All material was made from undoped metal.

TABLE VI

PHYSICAL CONDITION OF PRODUCER A TUNGSTEN

Surface finish measured with a profilometer is typically 150-200 microinches.

	Sheet Code	Nominal Thickness	Flatness (Maximum deviation from 12" straight edge)	Number of surface defects (typically .05 dia x.003 depth)	Total defect area indicated by ultrasonic inspection (In^2)
Sheet 7" x 11-1/2"	A I A	.051	.10	0	0
	A II A	.051	.12	0	0
	A III A	.056	.11	0	0
	A I B	.051	.11	1	.005
	A II B	.052	.09	12	.06
	A III B	.052	.10	0	50
	A I C	.053	.09	1	0
	A II C	.051	.10	1	0
	A III C	.052	.10	0	4
Bar 1-1/8" X 11-1/2"	A IV A	.254	-	0	0
	A IV B	.242	.02	0	0
	A IV C	.258	.03	0	0

TABLE VII

PHYSICAL CONDITION OF PRODUCER B TUNGSTEN

Surface Finish Ranged from a Minimum of 60 to a Maximum of 200 Microinches

	Specimen	Nominal Thickness	Flatness (Maximum deviation from 12" straight edge)	Number of surface defects (typically .05" dia x .003" depth)	Ultrasonic inspection (Number of defects .004 sq. in. or less)
SHEET 7.0" x 11.5"	B I A	.051	.07	0	0
	B I B	.050	.17	0	1
	B I C	.051	.19	0	0
	B II A	.049	.11	0	3
	B II B	.048	.13	area of defect covering 2 sq. in.	8
	B II C	.051	.15	received cracked	-
	B III A	.050	.11	6	0
	B III B	.051	.12	crystallized surface appearance	2
	B III C	.047	.10	6	0
	B V A	.053	.05	0	0
	B V B	.048	.06	0	0
SHEET 1.12" x 11.5"	B IV B c	.242	0	0	0
	B IV B b	.240	.02	4	0
	B IV B a	.245	.02	0	0
	B IV 3 a	.248	.14	2	0
	B IV 3 b	.248	.13	3	0
	B IV 3 c	.252	.13	4	0
	B IV 4 a	.247	.03	4	0
	B IV 4 b	.248	.04	3	0
	B IV 4 c	.253	.03	3	0

Powder lot not identified by producer

TABLE VIII

PHYSICAL CONDITION OF PRODUCER C TUNGSTEN

Surface finish of sheet is typically 60 microinches as measured with a profilometer except sheets C III C a and C III B b which are 135 micro-inches, and bar which are about 100 microinches.

	Sheet Code	Nominal Thickness	Flatness (Maximum deviation from 12" straight edge)	Number of surface defects	Total defect area indicated by ultrasonic inspection
SHEET 3-1/2 x 11-1/2	C I A a	.052	.04	0	0
	C I A b	.052	.05	0	0
	C I B a	.051	.04	0	0
	C I B b	.053	.05	0	0
	C I C a	.052	.04	cracked	-
	C I C b	.053	.16	0	0
	C II A a	.054	.04	0	0
	C II A b	.051	.02	0	0
	C II B a	.047	.10	4	0
	C II B b	.050	.09	1	0
	C II C a	.047	.09	0	.55 sq. in.
	C II C b	.053	.15	0	.7 sq. in.
	C III A a	.052	.21	0	0
	C III A b	.052	.13	0	0
	C III B a	.052	.03	0	0
	C III B b	.053	.03	0	0
	C III C a	.047	.12	cracked	-
	C III C b	.047	.12 (8" span)	0	0
BAR 1-3/8 x 11-1/2	C IV A a	.250	.02	0	-
	C IV A b	.256	.02	1	-
	C IV A c	.254	.02	0	-
	C IV B a	.246	.02	1	-
	C IV B b	.258	.02	0	-
	C IV B c	.260	.04	5	-
	C IV C c	.254	.02	2	-
	C IV C b	.253	.02	3	-
	C IV C c	.254	.01	0	-

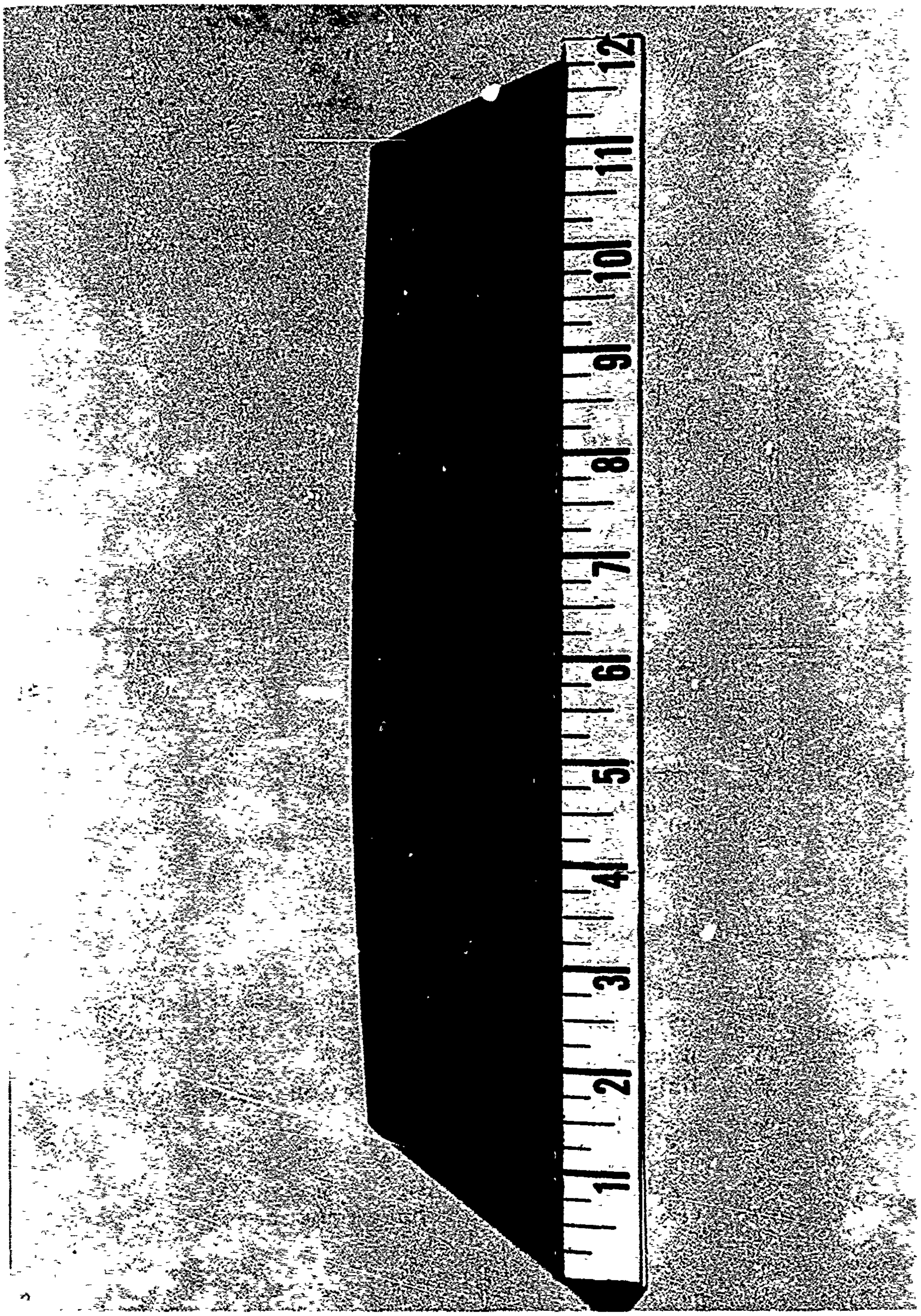


Figure 6. Sheet BIC As-Received

TABLE IX

TEST SPECIMENS CODING DESCRIPTION FOR TUNGSTEN

For example, specimen C II B - 5 is described below

C II B b - 5

5 — Position in sheet or bar

b — Used only when more than one piece of material with the same producer, condition and powder lot exists.

B — Powder lot (Three powder lots were ordered from each producer.)

II — Material condition
- I - .050 sheet, low cold reduction stress relieved
- II - .050 sheet, low cold reduction, as rolled
- III - .050 sheet, high cold reduction, stress relieved
- IV - .250 thick bar
- V - .050 sheet, high cold reduction, stress relieved

C — Producer (Material procured from three producers)

DESCRIPTION OF TENSILE TEST SPECIMENS

Since tungsten is a hard brittle material at room temperature, normal machining techniques are unsatisfactory for specimen fabrication and grinding is used.

During resistance heating, excessive temperature variation was found in the test section of the reduced test section tensile specimens shown in Figure 7. The gradient in the two inch center section of the .050 x .500 cross-section strip specimen shown in Figure 8 was studied with various heated lengths between the grips. It was found that the largest gradient exists at the lowest temperatures. A 1/2 to 1% temperature drop from the center of the test specimen to the extensometer gage points was used to insure failure of the specimen within the two inch gage length. To achieve this temperature drop, the constant area heated length of the test specimen is 7.0 inches at 2000°F and 5.25 inches at 3600°F.

The elevated temperature strip specimen was also adopted for use at room temperature since the reduced section specimen tended to fail at the radius and required much more time to fabricate. At room temperature the extensometer covers only two inches of the seven inch constant section of the strip specimen being tensile tested and failure outside the gage length may occur.

The .250 inch thick tungsten bars were cut into .100 inch wide tensile strip specimens. Thus the bar specimens were of a rectangular cross-section 0.250" x 0.100" x 11.5 inches long with the dimensional tolerances being similar to the sheet specimen shown in Figure 8.

The sheet cutting plans are shown in Figures 9, 10 and 11. All the sheet and bar tensile specimens were cut parallel to the rolling direction. Bend angle specimens are .500" wide x $\sim$1.7" long and were mostly taken from the unheated ends of tested tensile specimens and thus were stressed parallel to the rolling direction. Positions 2 through 9 shown in Figure 9 are bend specimens taken perpendicular to the rolling direction. Positions 10 and 15 in Figure 9 were for the reduced test section tensile specimen and all others were the .500" wide tensile strip specimens.

Large residual stresses were found to exist at the hot sheared edges of the Producer C sheet. After strips of approximately 1/8" width were cut from the 11-1/2" sides, the sheet warpage changed significantly. Table X gives the warpage of the as-received sheets and the final tensile specimens as cut.

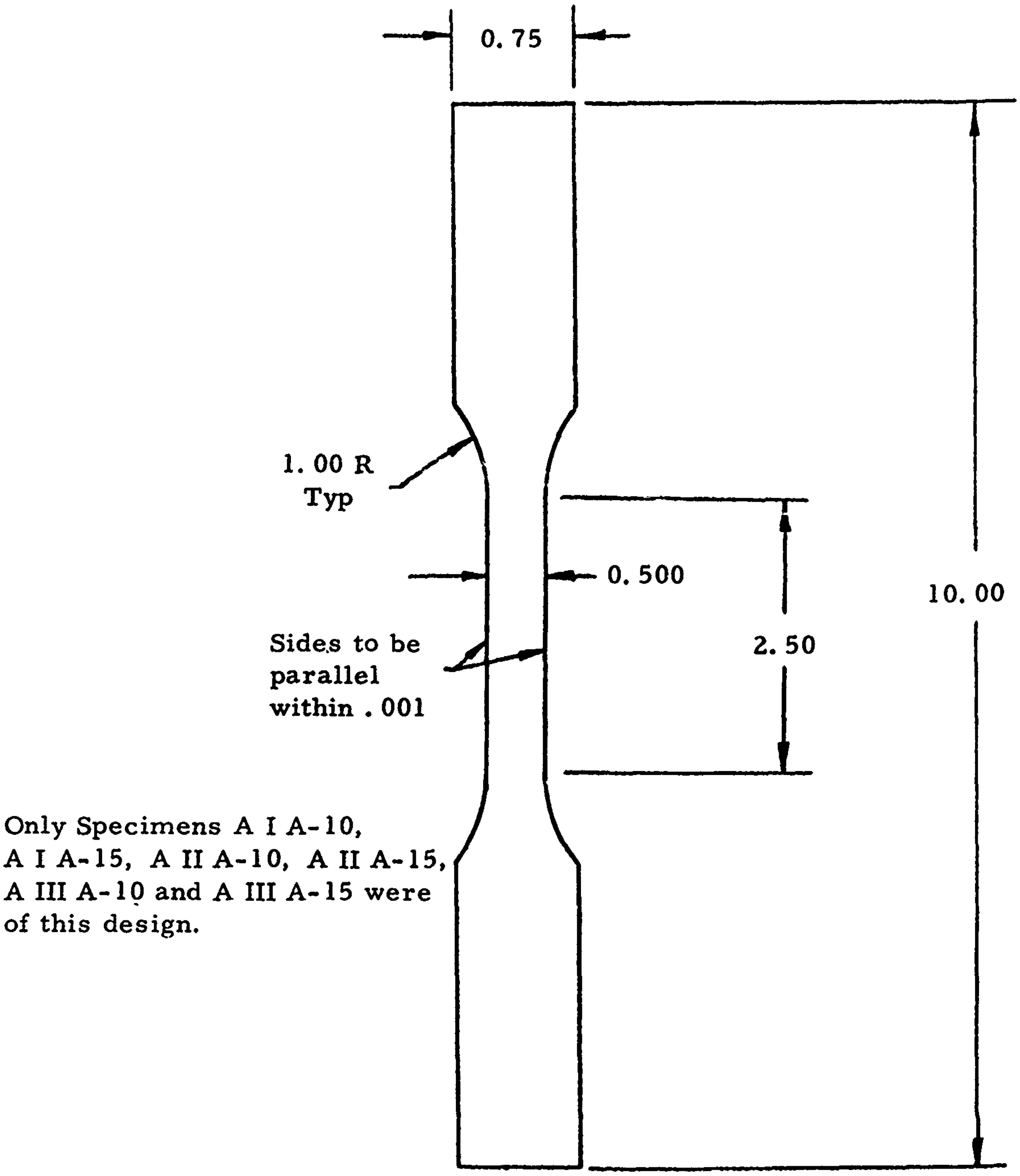


Figure 7. Reduced Test Section Tensile Specimen

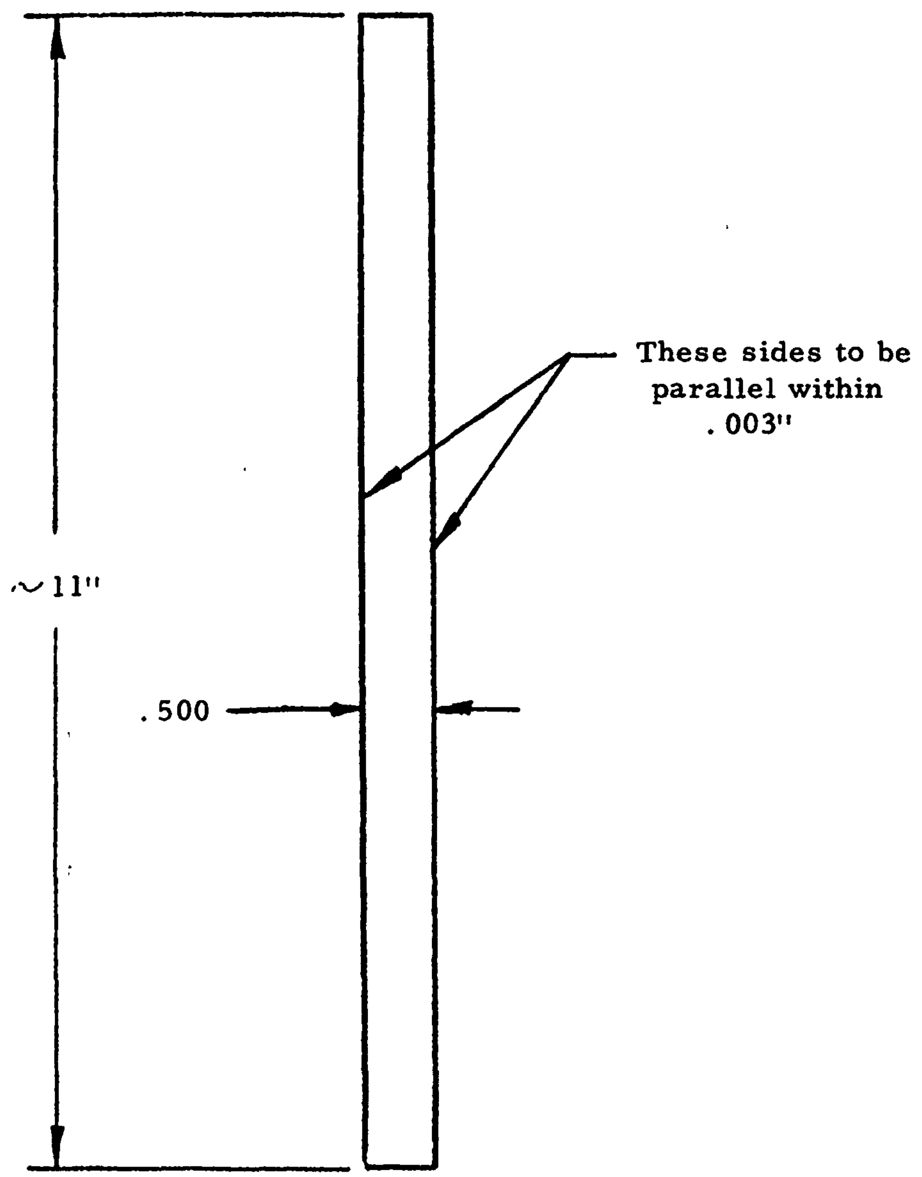


Figure 8. Tungsten Sheet Tensile Test Specimen

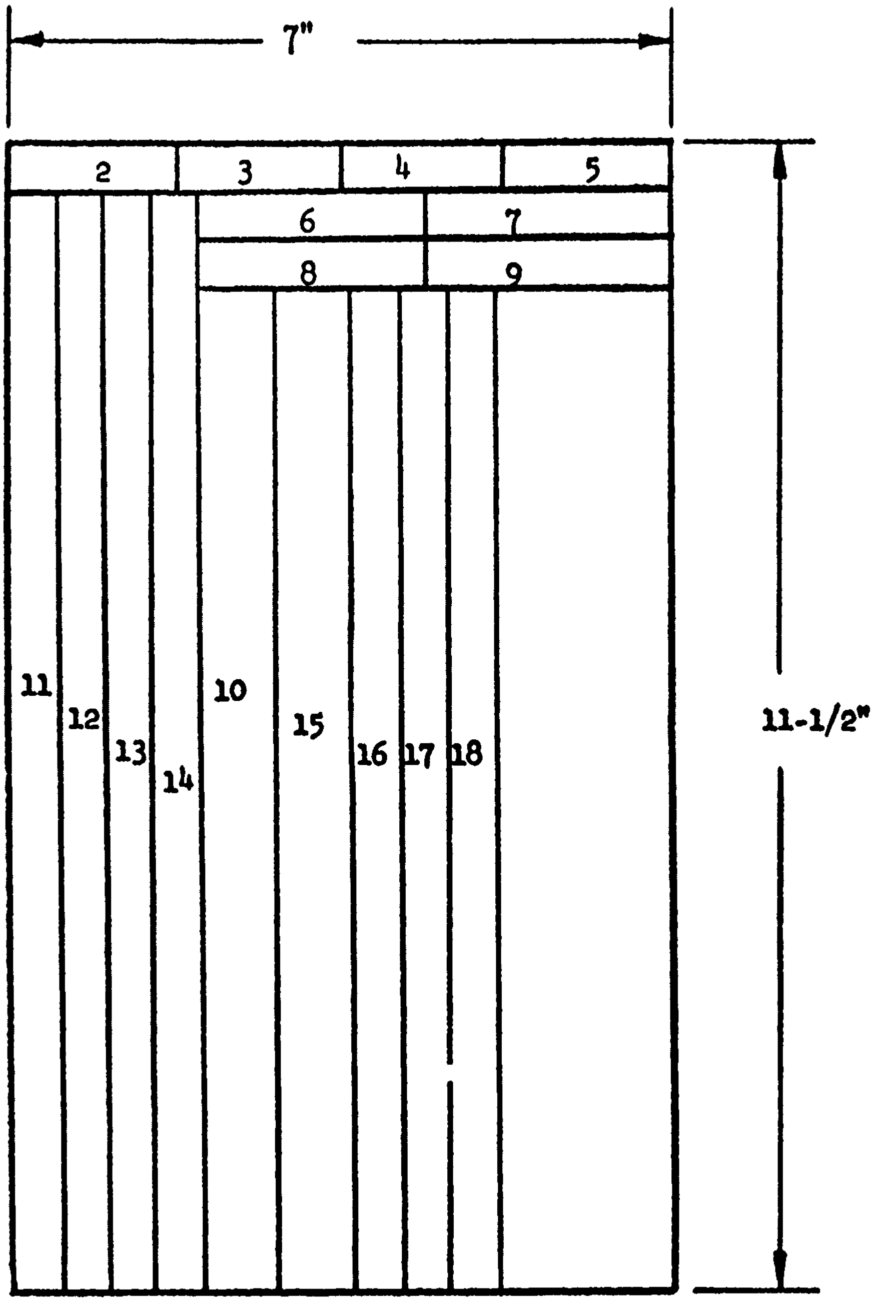


Figure 9. Test Specimen Cutting Plan - .050 Tungsten Sheet

Used for Sheets A I A, A II A, A III A, A I B, A II B and A III B

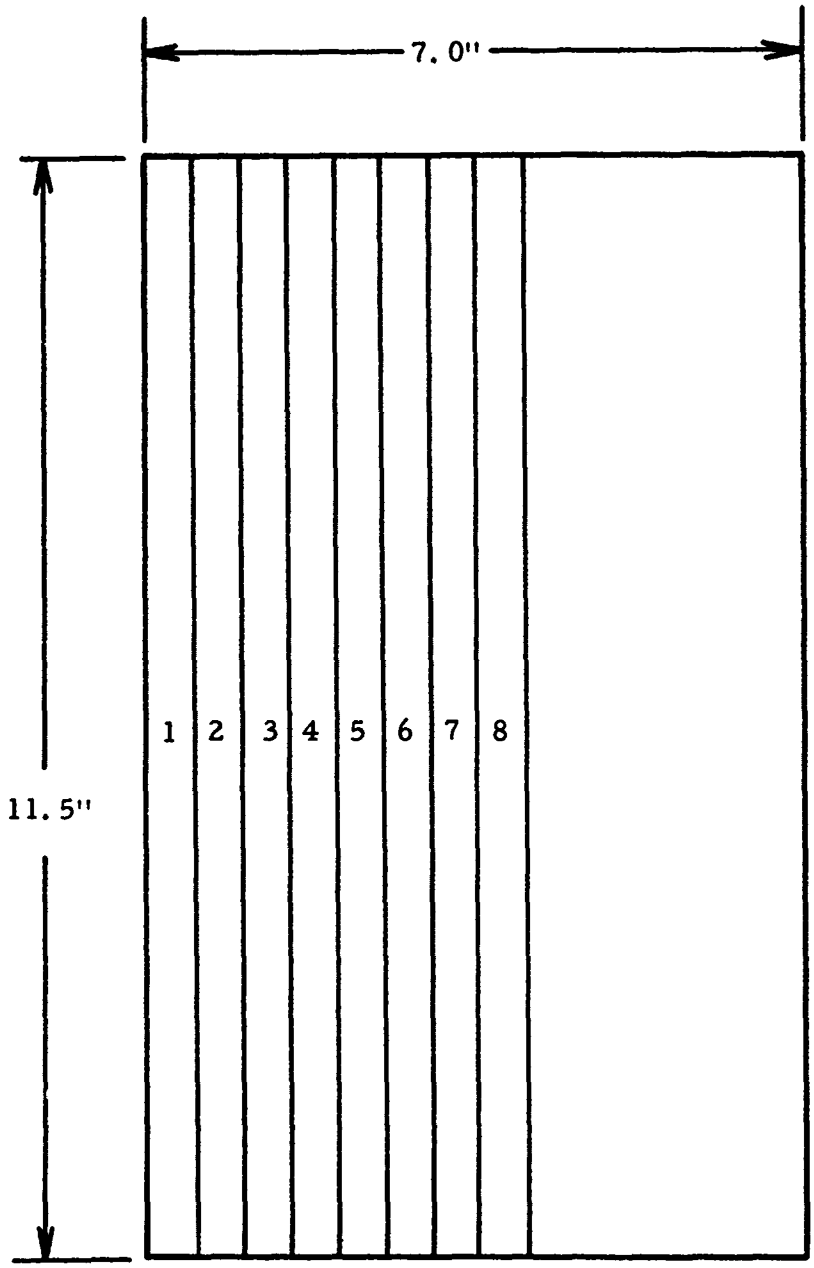


Figure 10. Tensile Strip Specimen Cutting Plan for Sheets:
A I C, A II C, A III C, B I A, B I B, B II A,
B III A, B III B, B III C, B V A, B V B.

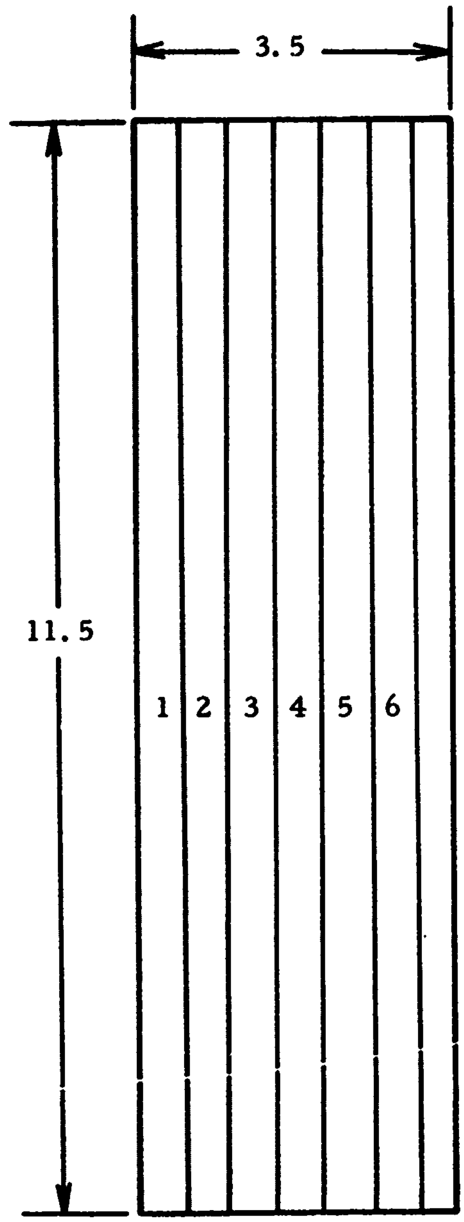


Figure 11. Tensile Strip Specimen Cutting Plan
For Producer C Tungsten Sheet

TABLE X

TEST SPECIMEN FLATNESS* OF PRODUCER C SHEET

Sheet No.	Sheet	1	2	3	4	5	6
C I A a	.04	.26	.01	.01	.00	.01	.03
C I A b	.05	.01	.04	.04	.04	.03	.06
C I B a	.04	.04	.00	.00	.00	.00	.06
C I C b	.16	.22	.13	.12	.12	.12	.12
C II A a	.04	.06	.01	.01	.01	.01	.08
C II B a	.10	.23	.00	.04	.04	.06	.04
C II C a	.09	.17	.02	.03	.03	.00	.04
C III A b	.13	.10	.05	.05	.06	.06	.16
C III B a	.03	.10	.04	.04	.02	.01	.03
C III C a	.12	.09	.05	.05	-	-	-
C III C b	.12	.14	.09	.09	.09	.13	.13

* (inches)

Flatness was maximum measured over the full sheet or specimen span except sheet C III C b for which deviation was taken over an 8-inch span because of a shorter warpage wave length.

HARDNESS TESTS

Rockwell superficial hardness tests were conducted to determine the relationship between room temperature strength and hardness.

The Rockwell 45-N superficial hardness scale was used. Results are shown in Table XI. Test result data within sheets exhibited a high degree of scatter. Large differences in strength levels showed only small differences in hardness.

METALLOGRAPHY

Thirteen longitudinal section metallographic samples were taken from the as-received tungsten sheet and bar to determine grain structure. Murikami's etch was used for all metallographic specimens. Photomicrographs showing the structure of these specimens are presented in Figures 12 through 23. As expected comparison of grain structure with tensile strength showed that specimens with a fine elongated grain structure exhibited the highest tensile strength levels.

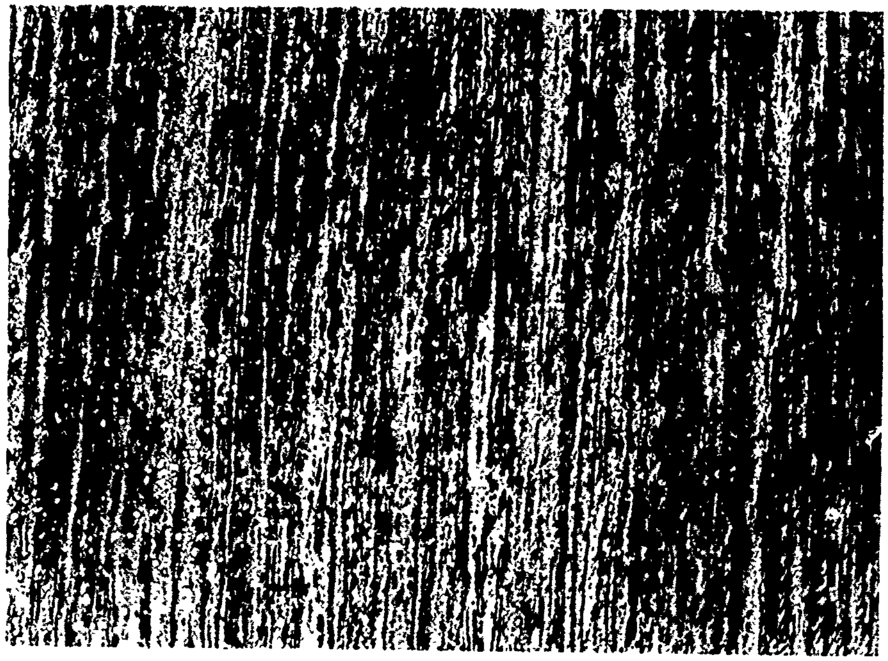


Figure 12. As-Received Tungsten Specimen AIIA-14. Longitudinal Section. X200 Specimen AIIIA-16. Has Essentially Identical Structure

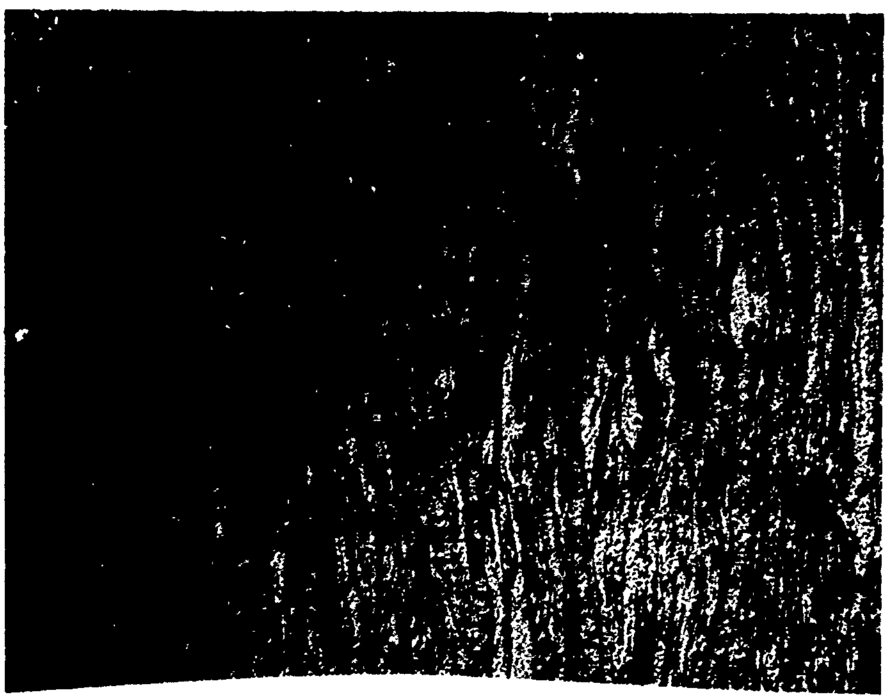


Figure 13. As-Received Tungsten Specimen AIIB-17. Longitudinal Section. X200

Figure 14. As-Received Tungsten Specimen AIVA
Longitudinal Section. X200

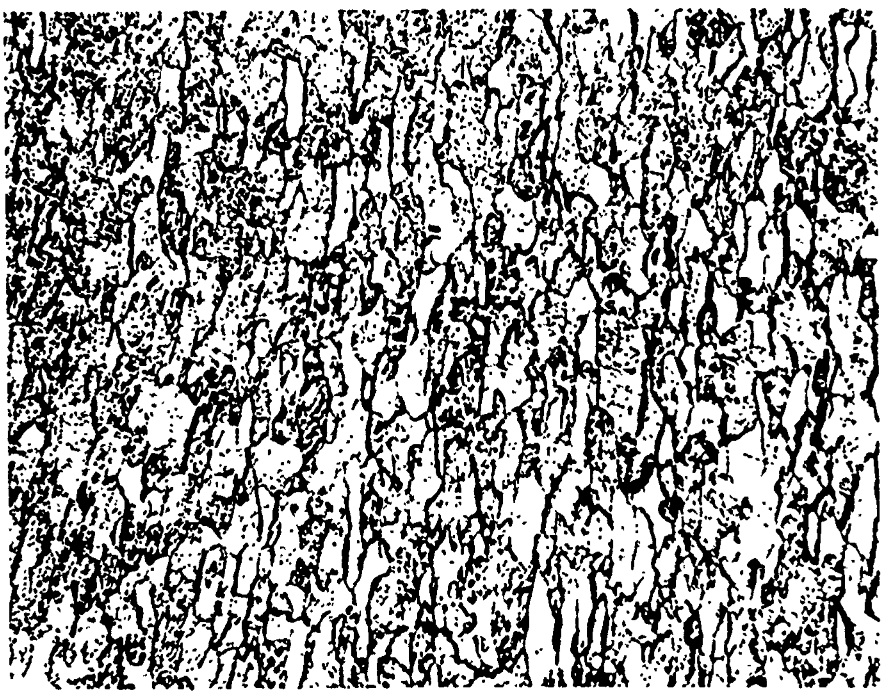


Figure 15. As-Received Tungsten Specimen BIA-2.
Longitudinal Section. X200

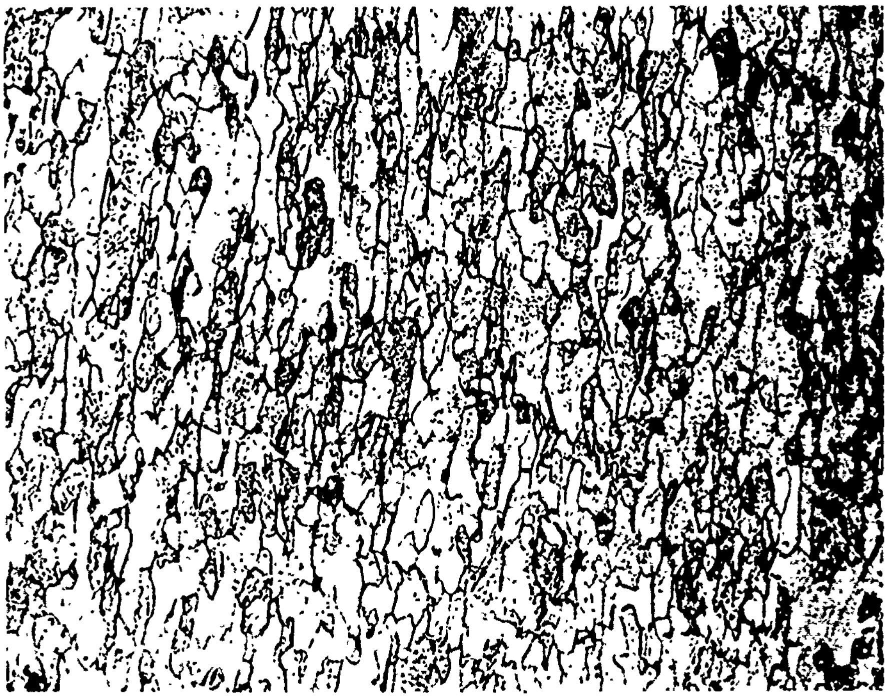


Figure 16. As-Received Tungsten Specimen BIIA-4. Longitudinal Section. X200

Figure 17. As-Received Tungsten Specimen BIIIA-1. Longitudinal Section. X200

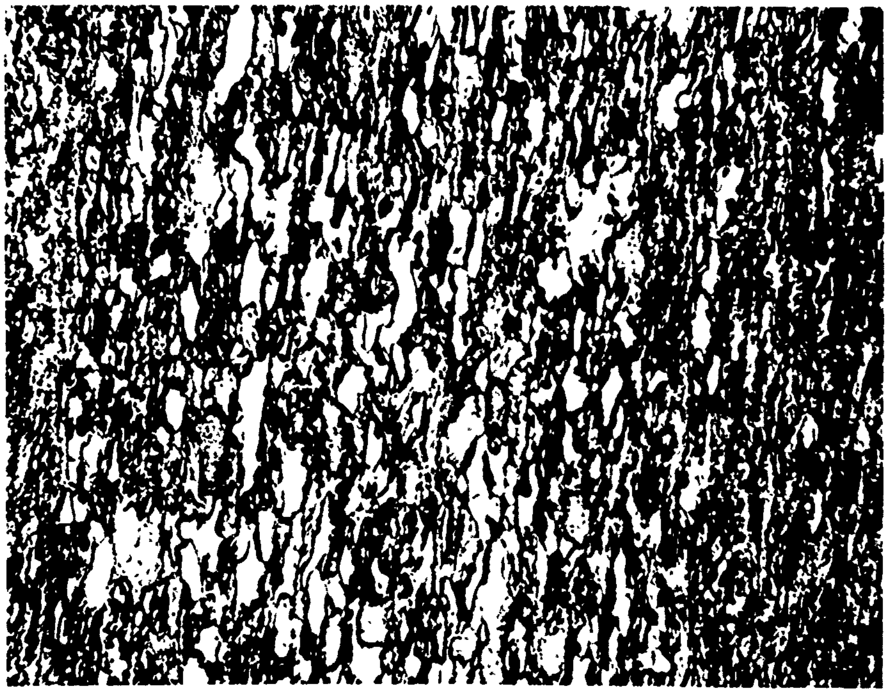


Figure 18. As-Received Tungsten Specimen BVA-6. Longitudinal Section. X200

Figure 19. As-Received Tungsten Specimen BIIIC-2. Longitudinal Section. X200

Figure 20. As-Received Tungsten Specimen (A_a-6. Longitudinal Section. X200

Figure 21. As-Received Tungsten Specimen CIIB_a-2. Longitudinal Section. X200

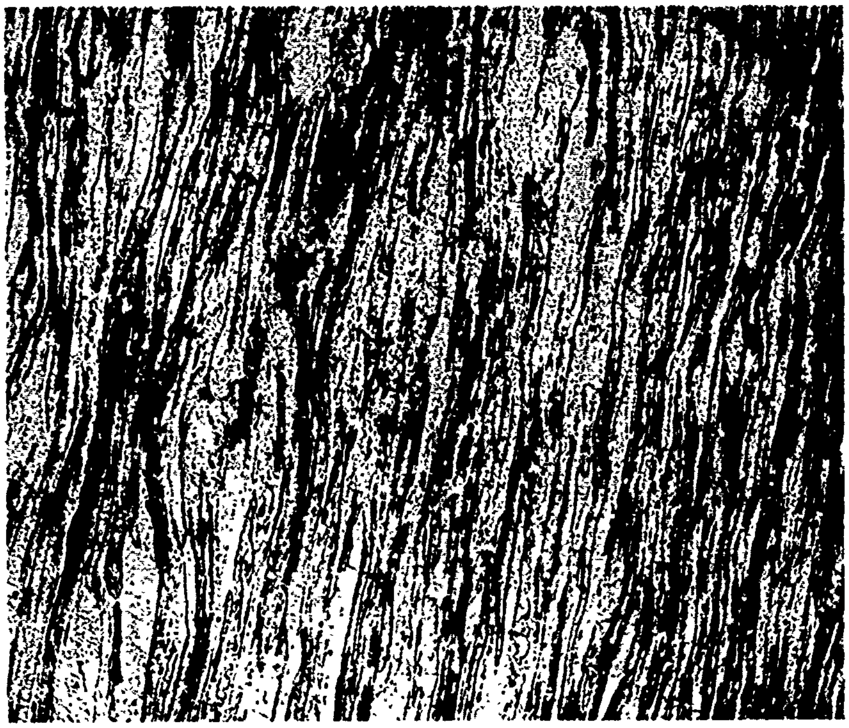


Figure 22. As-Received Tungsten Specimen $CIIIB_a$-4. Longitudinal Section. X200

Figure 23. As-Received Tungsten Specimen $CIIIC_b$-3. Longitudinal Section. X200

TABLE XI

SUPERFICIAL HARDNESS OF TUNGSTEN

Average of three values taken on as-received surfaces

Rockwell 45-N scale

A I A	49.4	
A II A	50.1	
A III A	48.7	
A II B	50.4	Average hardness = 50.2
A III B	51.6	Average R. T. Strength = 153.3 KSI
A I C	50.9	
A II C	48.8	
A III C	51.4	
A IV C	45.8	
B I A	44.1	
B II A	45.8	
B III A	46.9	Highest strength sheet of Producer B
B V A	45.5	
B II B	45.5	Average hardness = 45.1
B V B	45.4	Average R. T. Strength = 29.0 KSI
B I C	45.6	
B III B	37.7	Lowest strength sheet
B IV B a	43.1	
C I A	47.9	
C III A	48.4	
C I B	49.2	Average hardness = 48.1
C II C	47.6	Average R. T. Strength = 90.8 KSI
C III C	47.6	

FLEXURE TESTS - TRANSVERSE GRAIN

Twenty-three (23) transverse flexure tests on Producer A sheet material were performed. The test set up is shown in Figures 5 and 24. The only variable significantly affecting the bend angle is the radius of the loading bar. The 0.0625 radius chosen was relatively severe to enable bend evaluation at high ductility. Figure 25 shows the bend angle at failure versus the test temperature. Sheet A III A (high cold reduction) appears to have lower ductility in the 700° to 900°F range than A I A or A II A. All three sheets exhibited highest ductility at 700°F.

Deflection versus load curves were recorded for eleven of these tests and the flexural proportional limit stress computed. The proportional limit was chosen because it is the maximum stress at which the flexure stress formula is valid. Figure 26 shows the proportional limit stress versus temperature. Sheet A II A exhibited consistently lower proportional limit. This data is tabulated in Tables XII and XIII.

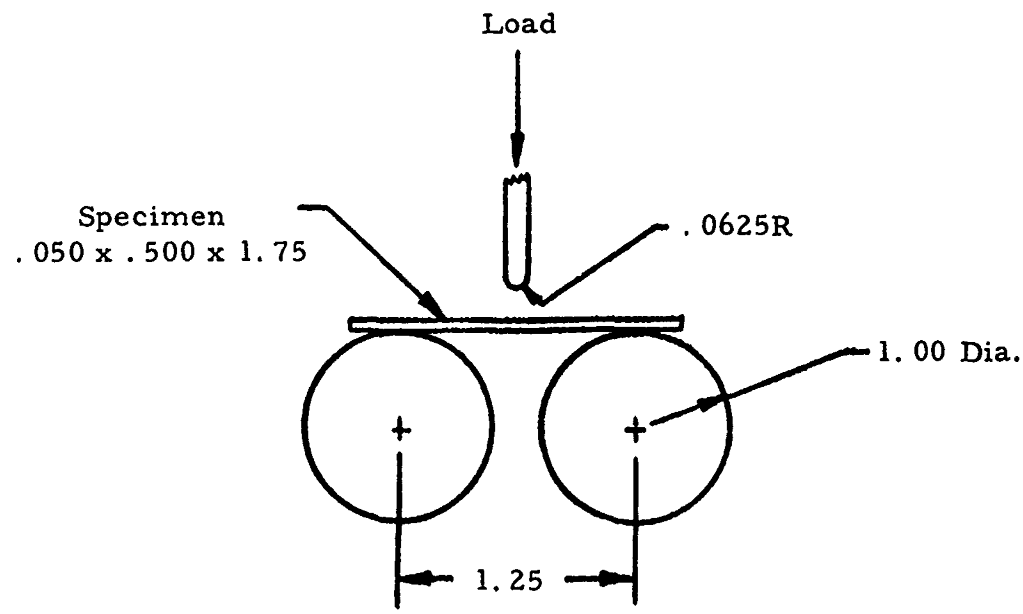


Figure 24. Bend Test Set Up

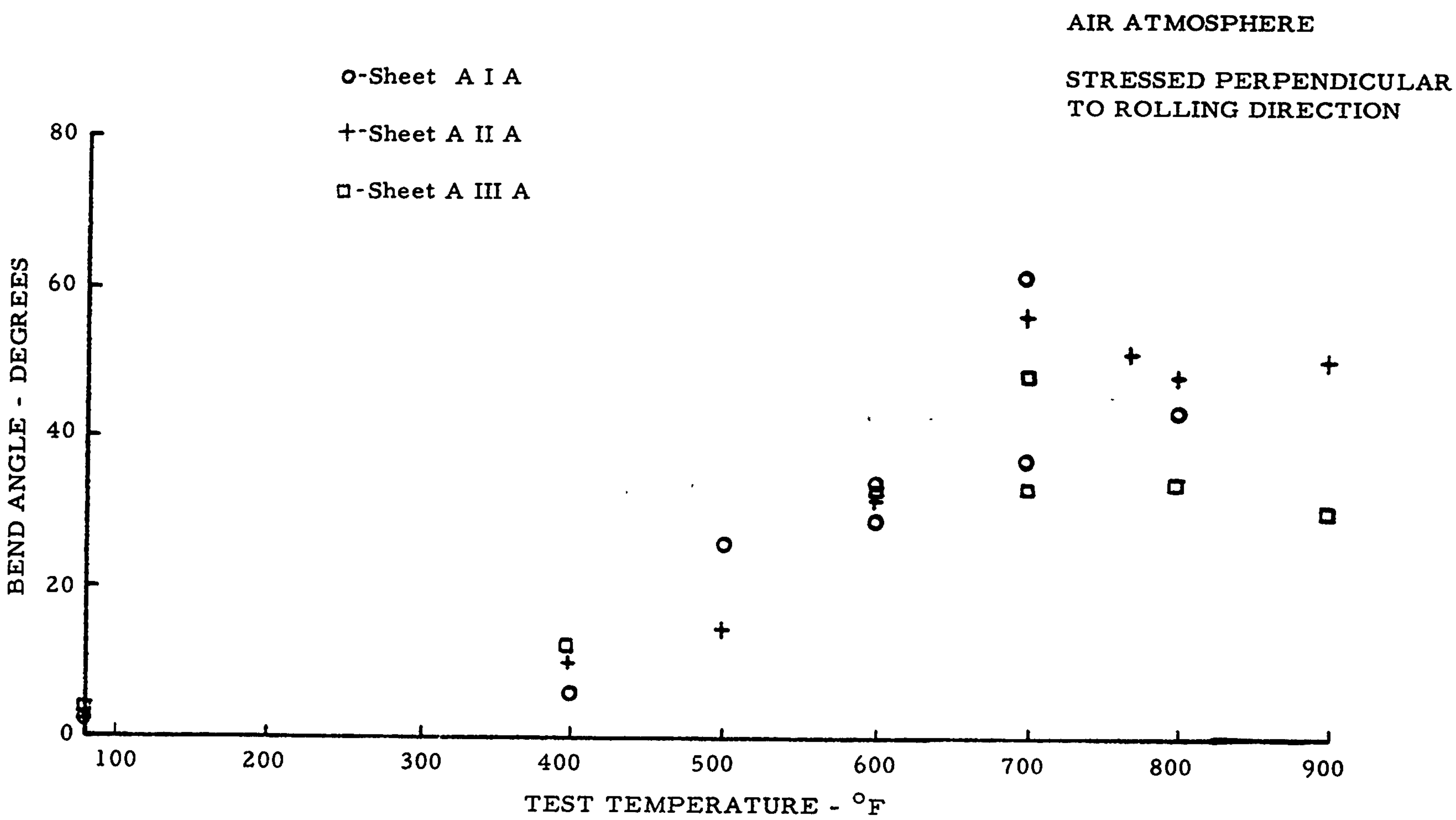


Figure 25. Bend Angle vs Test Temperature

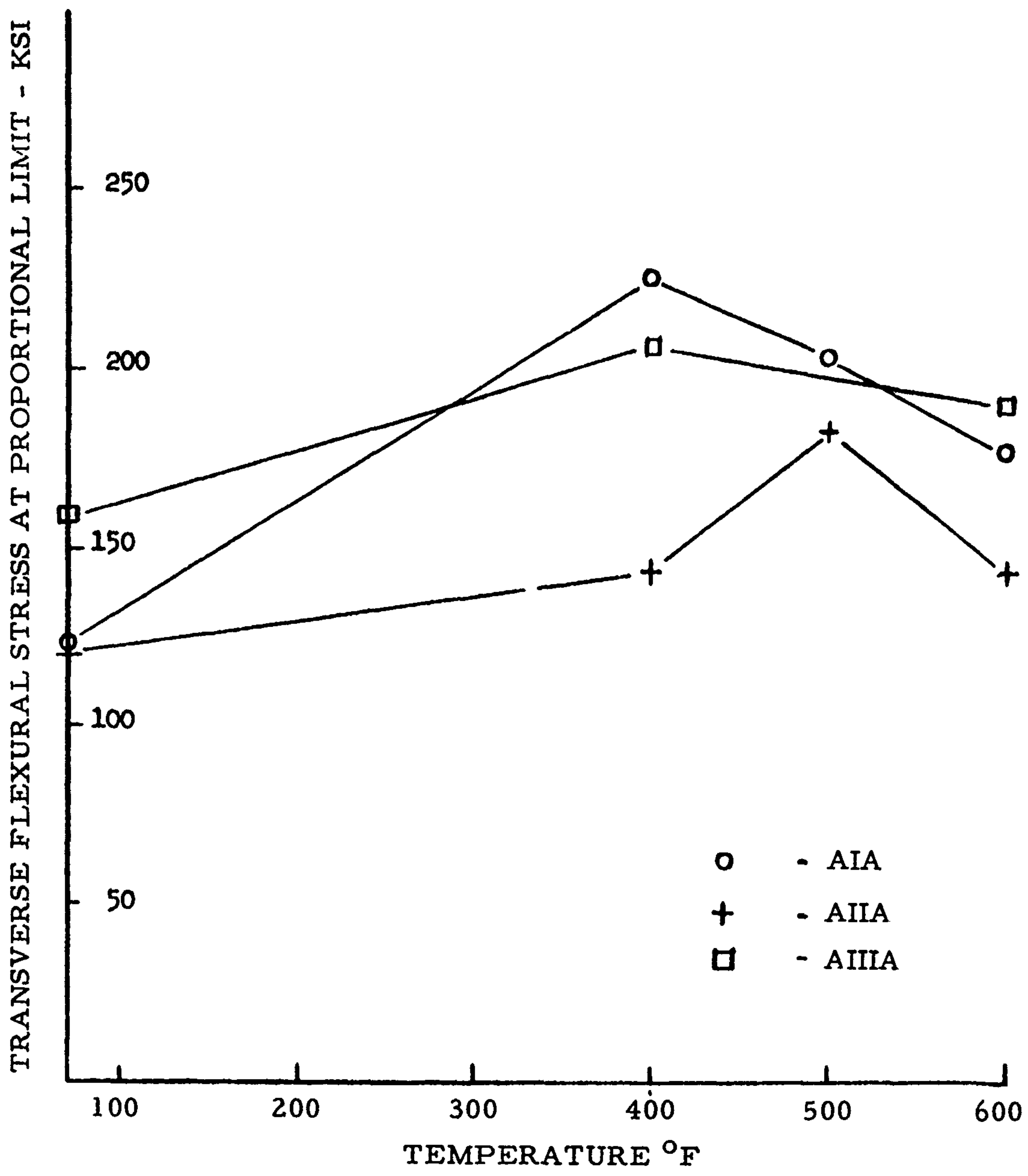


Figure 26. Transverse Flexural Stress at Proportional Limit vs Test Temperature

TABLE XII

BEND TEST DATA

Stressed transverse to rolling direction

Specimen No.	Temp. (^{o}F)	Proportional Limit (Lbs.)	Ultimate Load (Lbs.)	Bend Angle (Deg.) (after failure)	Proportional Limit Stress
A I A 2	R.T.	85	85	3.0	124,000
A I A 3	400°	155	155	6.5	226,000
A I A 4	500°	140	243	26.5	204,000
A I A 5	600°	120	203	29.0	178,000
A II A 2	R.T.	75	75	3.5	120,000
A II A 3	400°	100	100	10.0	143,500
A II A 4	500°	125	195	14.5	183,000
A II A 5	600°	100	225 NF	31.0 NF	143,500
A III A 3	400°	175	250	12.0	207,000
A III A 4	600°	160	280	33.5	1[illegible],000
A III A 5	R.T.	133	133	5.5	[illegible]38,[illegible]

NF = No Failure

TABLE XIII

BEND TEST DATA

Stressed transverse to rolling direction

SPECIMEN NO.	TEST TEMPERATURE °F	BEND ANGLE DEGREES
A I A 6	700	37
A I A 7	700	62
A I A 8	600	34
A I A 9	800	43
A II A 6	700	56
A II A 7	900	50
A II A 8	770	51
A II A 9	800	48
A III A 6	700	48
A III A 7	800	34
A III A 8	900	30
A III A 9	700	33

FLEXURE TESTS - LONGITUDINAL GRAIN

These flexure specimens were cut from the unheated ends of the failed tensile specimens, and thus were stressed parallel to the sheet rolling direction. Most of the tests were conducted at room temperature and 300°F. The test data is shown in Tables XIV through XIX and the summaries of the average values are given in Tables XX through XXIII.

Flexure strength values, summarized in Table XX for Producer A material, tested at room temperature, indicated that powder lot caused little variation. However, the 300°F bend angle tests, summarized in Table XXI indicates that powder lot A showed better ductility. The bend tests on sheet A III B showed that the high degree of internal delamination previously indicated by ultrasonic inspection is correct.

TABLE XIV

FLEXURE TESTS OF PRODUCER A TUNGSTEN AT ROOM TEMPERATURE

0.0625 radius loading bar
0.5 in./min deflection rate

Specimen No.	Flexure Strength (KSI)
A I A 17	239
A I A 18	220
A I A 16	286
A II A 18	294
A II A 16	405
A II A 17	187
A III A 18	264
A III A 17	350
A III A 17	368
A I B 12	291
A I B 12	171
A I B 14	201
A II B 12	362
A II B 13	324
A II B 18	264
A III B 11	316
A III B 17	313
A III B 17	305
A I C 6	277
A I C 3	223
A I C 4	260
A II C 1	230
A II C 5	197
A II C 2	238
A III C 4	382
A III C 6	362
A III C 3	331
A IV B 1	57
A IV B 3	46
A IV B 5	41
A IV C 1	97
A IV C 2	129
A IV C 4	170

TABLE XV

BEND TRANSITION TEMPERATURE TESTS
PRODUCER A

0.0625 radius loading bar
Deflection rate 0.5 in./min. at start
increased to 2 in./min. at end of test

Specimen No.	Test Temperature (^{o}F)	Bend Angle (Degrees)
A I A 11	200	45
A I A 12	250	74
A I A 13	300	90
A I A 17	300	144 No failure
A II A 12	200	< 4
A II A 13	250	36
A II A 13	300	146 No failure
A II A 17	300	99
A III A 12	200	29
A III A 13	250	85
A III A 18	300	131
A III A 14	300	144 No failure
A I B 16	300	110
A I B 17	300	77
A II B 14	250	10
A II B 13	300	147
A II B 14	300	38
A III B 14	200	19 Delaminated
A III B 14	250	5 Delaminated
A III B 18	300	58
A III B 11	350	88
A III B 12	350	63
A III B 16	350	22
A III B 18	350	102
A III B 14	330	27 Delaminated
A I C 4	300	74
A I C 5	300	64
A II C 2	300	99
A II C 6	300	93
A III C 2	300	51 Delaminated
A III C 5	300	77

TABLE XVI

FLEXURE TESTS OF PRODUCER B TUNGSTEN

0. 0625 radius leading bar
0. 5 in. /min. deflection rate
Bend angles were all less than
4° except as noted.

Specimen No.	Temperature °F	Flexure Strength KSI
B I A 5	RT	26
B I A 5	300	156
B II A 4	RT	141
B II A 4	300	64
B III A 1	RT	178
B III A 2	RT	175
B III A 3	RT	168
B III A 7	RT	57
B III A 1	300	168
B III A 2	350	- Bend Angle 32°
B III A 4	350	- Bend Angle <4
B III A 4	375	- Bend Angle 128 no failure
B III A 7	375	- Bend Angle 29
B V A 6	RT	105
B V A 6	300	102
B II B 7	RT	46
B II B 7	300	103
B V B 6	RT	102
B V B 3	RT	98
B V B 7	RT	111
B V B 7	RT	91
B V B 6	300	124 Bend Angle 6°
B III C 2	RT	48
B III C 2	300	62
B IV B a-1	RT	85
B IV B a-4	RT	84
B IV B a-5	RT	52

TABLE XVII

FLEXURE TESTS OF PRODUCER C

TUNGSTEN SHEET AT ROOM TEMPERATURE

Specimen	Flexure Strength (KSI)
C I A a-4	135
-5	65
-6	130
C I B a-4	120
-5	118
-6	108
C I C b-4	103
-5	107
-6	94
C II A a-4	115
-5	153
-6	116
C II B a-3	123
-5	141
-6	124
C II C a-3	108
-4	126
-6	97
C III A b-4	172
-5	148
-6	144
C III B a-4	221
-5	165
-6	180
C III C a-1	214
-2	240
-3	132
C III C b-2	98
-5	220
-6	143

TABLE XVIII

FLEXURE TESTS OF PRODUCER C TUNGSTEN SHEET AT 300°F

Specimen	Flexure Strength (KSI)	Bend Angle (Degrees)
C I A a-1	112	< 4
-2	149	4.5
C I B a-1	145	< 4
-2	176	< 4
C I C b-1	141	< 4
-2	192	5.0
C II A a-1	122	< 4
-2	153	< 4
C II B a-1	123	6.5
-2	212	6.0
C II C c-1	148	< 4
-2	158	< 4
C III A b-1	197	< 4
-3	224	5.5
C III B a-1	297	< 4
-2	275	< 4
C III C a-1	-	18
-2	-	31
C III C b-1	134	< 4
-3	251	< 4

TABLE XIX

BEND TRANSITION TEMPERATURE TESTS OF PRODUCER C TUNGSTEN

SPECIMEN NO.	TEMPERATURE (°F)	BEND ANGLE (DEGREES)
C I A a-6	350	5
C I A a-2	375	6
C I A a-3	400	<4
C II B a-6	350	<4
C II B a-1	400	5
C II B a-4	400	8
C III C a-3	350	146 No failure
C III C a-1	350	84
C III C a-3	350	148 No failure
C III C b-1	350	7
C III C b-2	350	<4
C III C b-3	350	<4

TABLE XX

AVERAGE ROOM TEMPERATURE FLEXURE STRENGTH*

FOR PRODUCER A TUNGSTEN

	Powder Lot			Average of Lots A, B, C
	A	B	C	
I 20% cold reduction 1830°F stress relief	248	221	253	241
II 20% cold reduction as-rolled	295	317	222	278
III 50% cold reduction 1830°F stress relief	327	311	358	332
Average of Groups I, II, III	290	283	278	284

*KSI

TABLE XXI

AVERAGE 300°F BEND ANGLES FOR PRODUCER A TUNGSTEN

Bend angles shown are degrees

	Powder Lot			Average of Lots A, B, C
	A	B	C	
I 20% cold reduction 1830°F stress relief	117	93	79	96
II 20% cold reduction as-rolled	122	92	96	103
III 50% cold reduction 1830°F stress relief	137	58	64	86
Average of Groups I, II, III	125	81	80	95

TABLE XXII

AVERAGE ROOM TEMPERATURE FLEXURE STRENGTH[1] OF PRODUCER C TUNGSTEN

	Powder Lot			Average of Lots
	A	B	C	A, B, C
I Low cold reduction stress relieved	109.9	115.3	101.3	108.8
II Low cold reduction as-rolled	128.0	129.3	110.3	122.5
III High cold reduction stress relieved	154.7	188.8	195.3[2]	179.6
Average of Groups I, II, III	130.9	144.5	135.6	137.0

(1) KSI

(2) Sheet C III C a; sheet C III C b results not included.

TABLE XXIII

AVERAGE 300°F FLEXURE STRENGTH* OF PRODUCER C TUNGSTEN

	Powder Lot			Average of Lots A, B, C
	A	B	C	
I Low cold reduction stress relieved	130.5	160.5	166.5	152.5
II Low cold reduction as-rolled	137.5	167.5	153.0	152.7
III High cold reduction stress relieved	210.5	286.0	-	-
Average of Groups I, II, III	159.5	204.7	-	-

*KSI

TENSILE TESTS

Tensile tests were conducted at room temperature, 2000°F and 3600°F. The tensile testing conditions are described in Table XXIV. The tensile test results on the .050 tungsten sheet and the .250 sheet bar are shown in Tables XXV through XXXVI.

Difficulties were encountered in successfully conducting tensile tests on all bar material and also the Producer B sheet material at 2000°F. The test specimens are near room temperature at the grip and for these materials the room temperature strength is apparently much less than the 2000°F strength. This condition was partially circumvented by increasing the grip temperatures.

No evidence of ductility was found at room temperature. Material exhibiting less than ~80,000 psi tensile strength at room temperature showed a high incidence of breakage during handling and specimen fabrication. In some cases low strength combined with specimen warpage led to fracture when the material was clamped flat. The full complement of tensile tests were not conducted for these materials because of large scatter and difficulties in conducting the tests successfully. All the bar material exhibited a low degree of cold reduction. Unfortunately, all the sheet material supplied by Producer B exhibited low strength with large scatter such that little useful information could be deducted concerning the level of cold reduction. Producer B reported that both the 60% and 90% cold reduction sheets were stress relieved at 2460°F, 20 minutes. It is believed that this was the brightness temperature as measured with an optical pyrometer and the true temperature was actually about 2650°F. Recrystallization progresses at a rapid rate at 2650°F. Fracture appearance of the room temperature tests of the Producer A tungsten was typically jagged and lamirated whereas the Producer B tungsten was silky and showed no visual signs of laminations. Producer C material fell between these extremes.

Typical stress-strain curves are presented in Figures 27 through 35. The stress-strain curves as generated by the equipment have irregularities which have been attributed to non-linearities in the strain measurement system and small frictional loads in the loading train. These stress-strain curves are shown without irregularities for clarity and ease of presentation.

There were several cases where one sheet of material displayed distinctly lower tensile properties than others from the same source. These values were not included in the averages since it was believed that these deviations were attributable to improper processing during fabrication of the sheets. Sheet B III B as noted in Table XXIX showed a much lower tensile strength than the other Producer B sheets at 2000°F. Sheet C III C b showed a very low room temperature tensile strength as shown in Table XXXI.

The $2000^{\circ}F$ strength of this sheet did not show any deviation from the other sheets indicating that the room temperature specimens may have been cracked prior to testing.

Tensile strength averages are presented in block form in Tables XXXVII through XLIII to facilitate distinction between the effects of production fabrication conditions and starting powder lots. These Tables indicate that the fabrication conditions are of greater importance than the powder lots.

A summary of average tensile properties of all the tests conducted are broken down by producer and form (sheet and bar). This summary is shown in Table XLIV. Each value shown for the sheet material is an average of up to 18 tests and for the bar material up to six tests.

The averages given in Table XLIV are graphed against temperatures in Figures 36 through 39. Figure 36, of Tensile Strength of .050 sheet vs Temperature clearly shows that the three producers supplied material in three distinctly different levels of cold work. Figure 37, of Tensile Strength of .250" thick sheet bar as a function of Temperature indicates that the three producers achieved similar cold reduction levels.

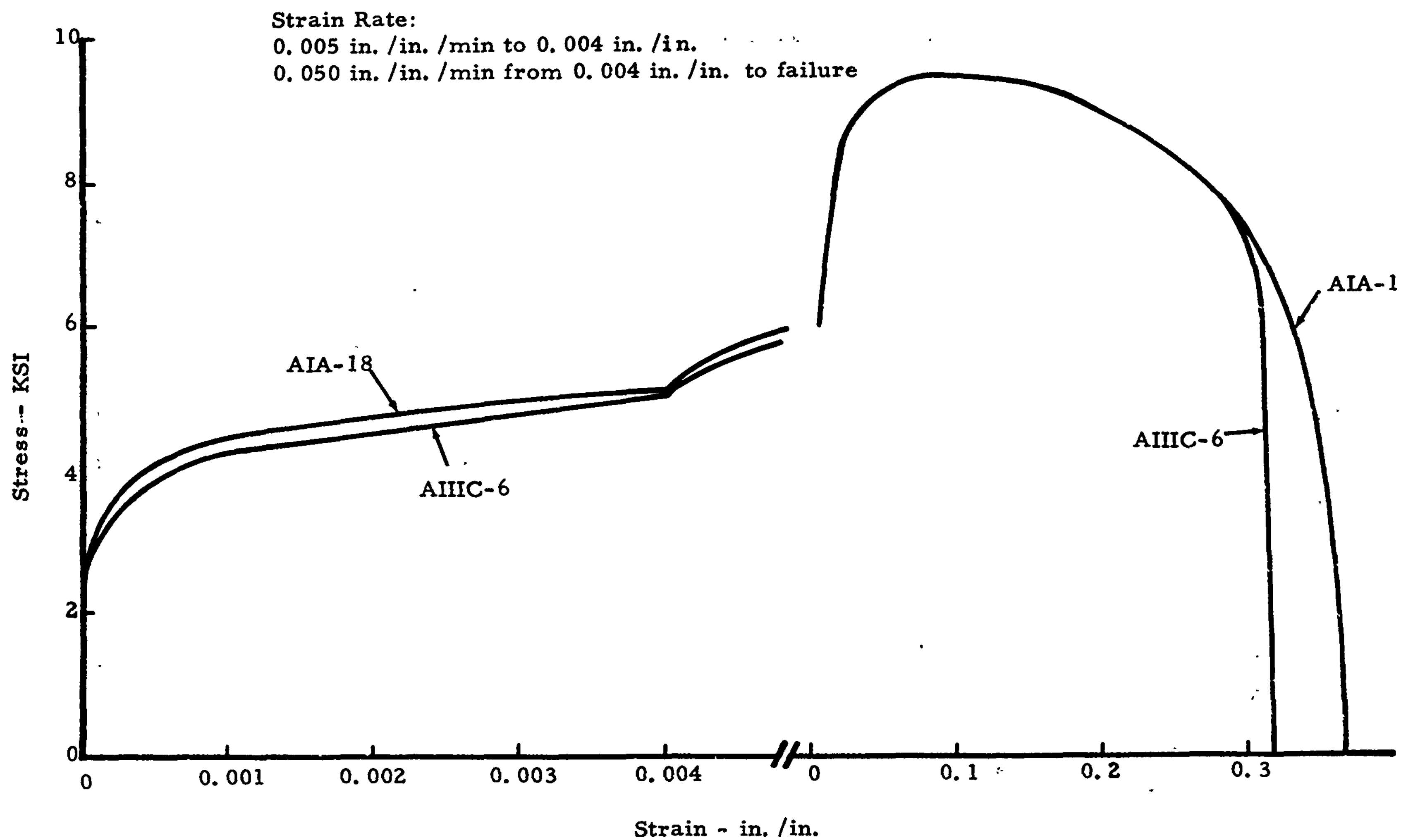


Figure 27. Stress-Strain Curves for Specimens AIA-18 and AIIC-6 at 3600°F

Strain Rate:
0. 005 in. /in. /min to 0. 004 in. /in.
0. 050 in. /in. /min from 0. 004 in. /in. to failure

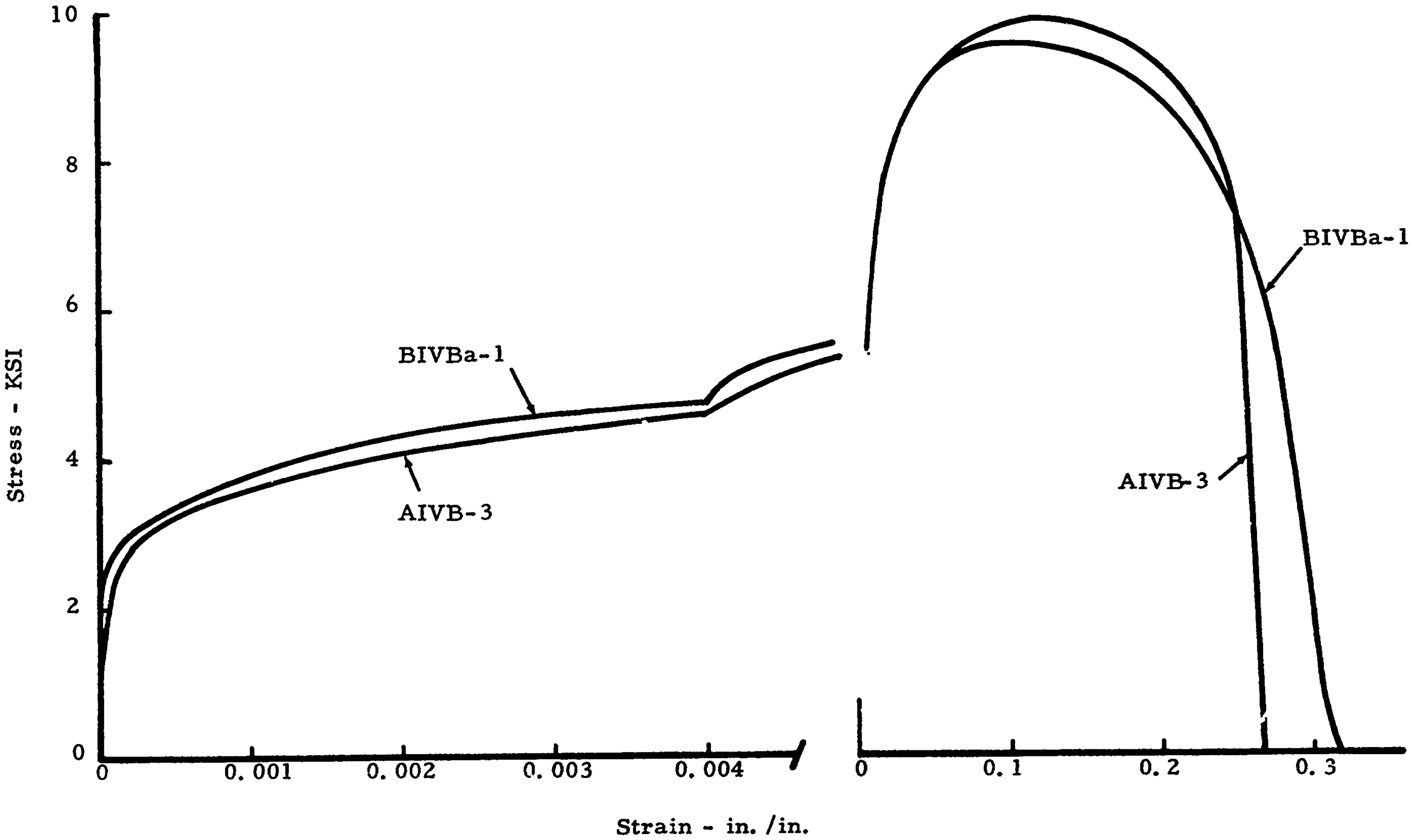


Figure 28. Stress-Strain Curve for AIVB-3 at 3600°F

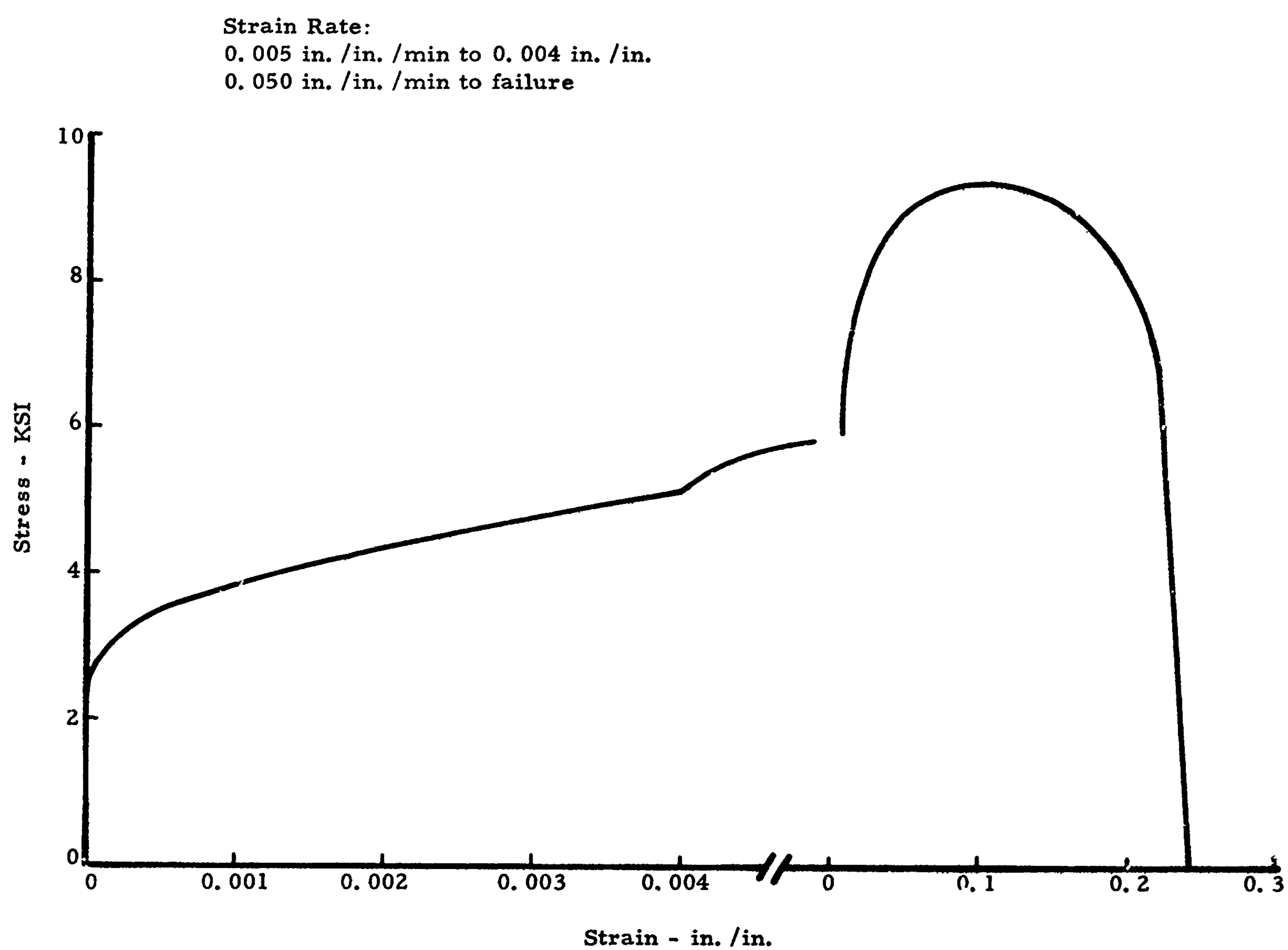


Figure 29. Stress-Strain Curve for BIIIA-2 at 3600°F

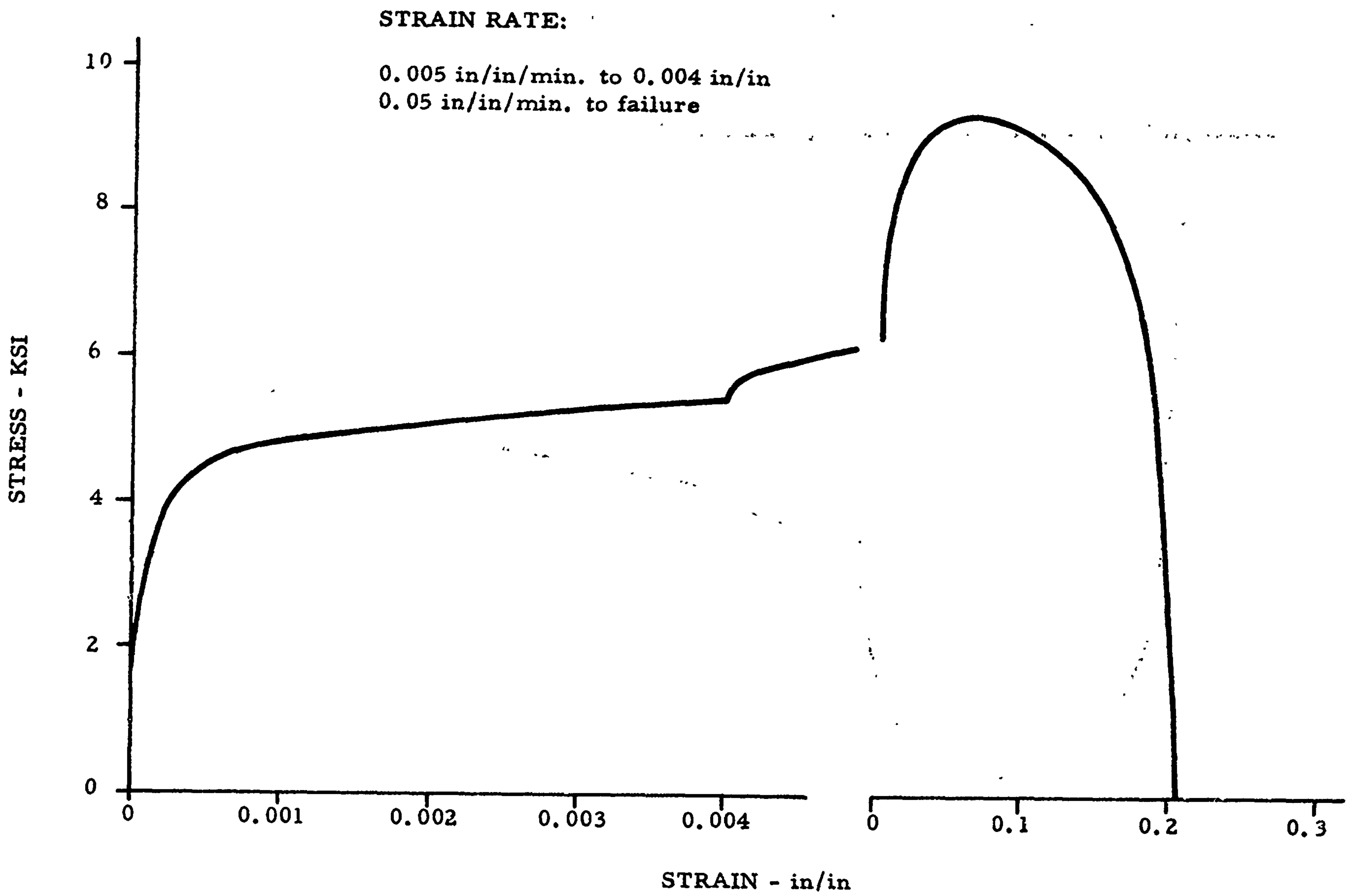


Figure 30. Stress-Strain Curve for CIIICb-6 at 3600°F

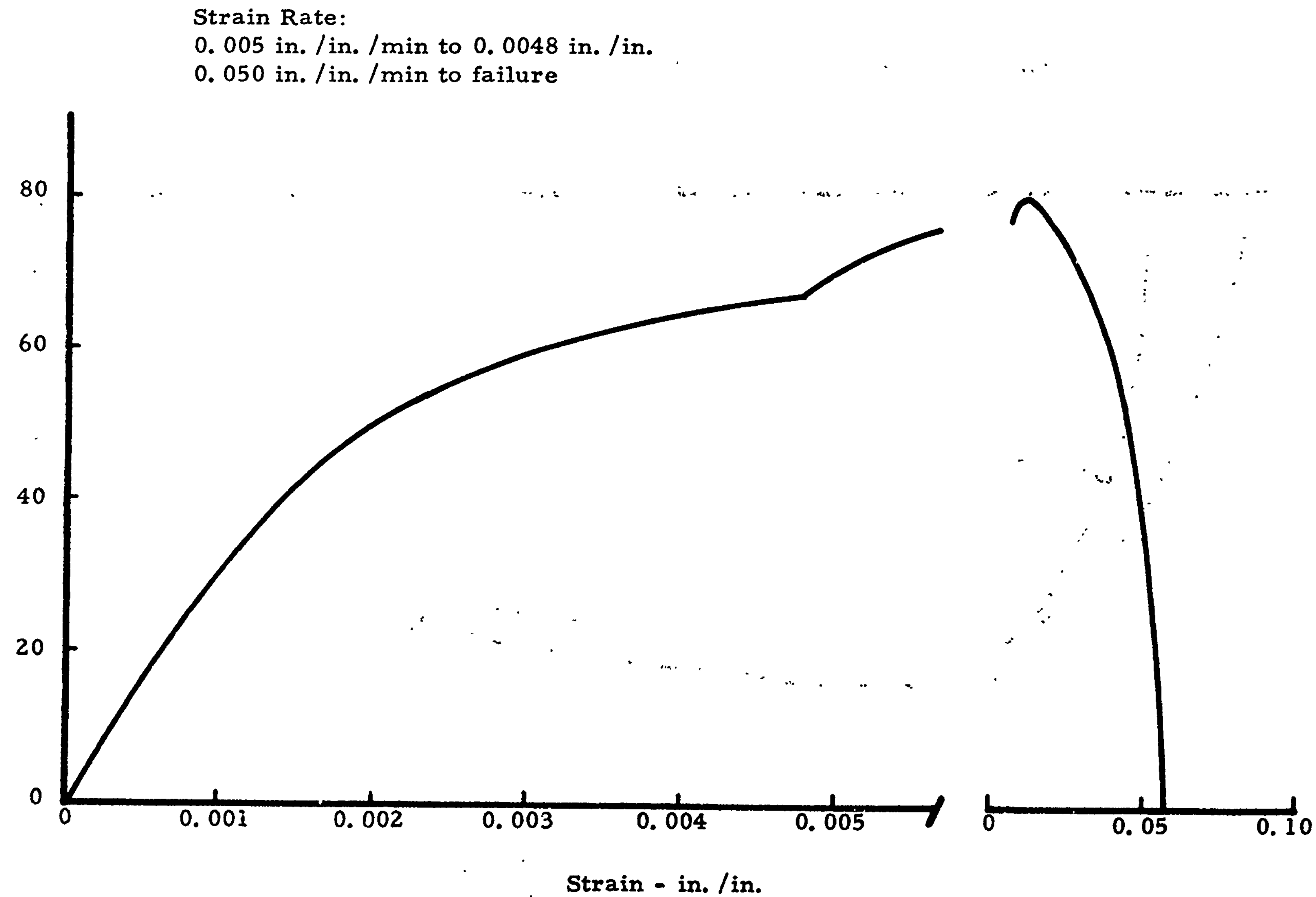


Figure 31. Stress-Strain Curve for Specimen AIIA-16 at 2000°F

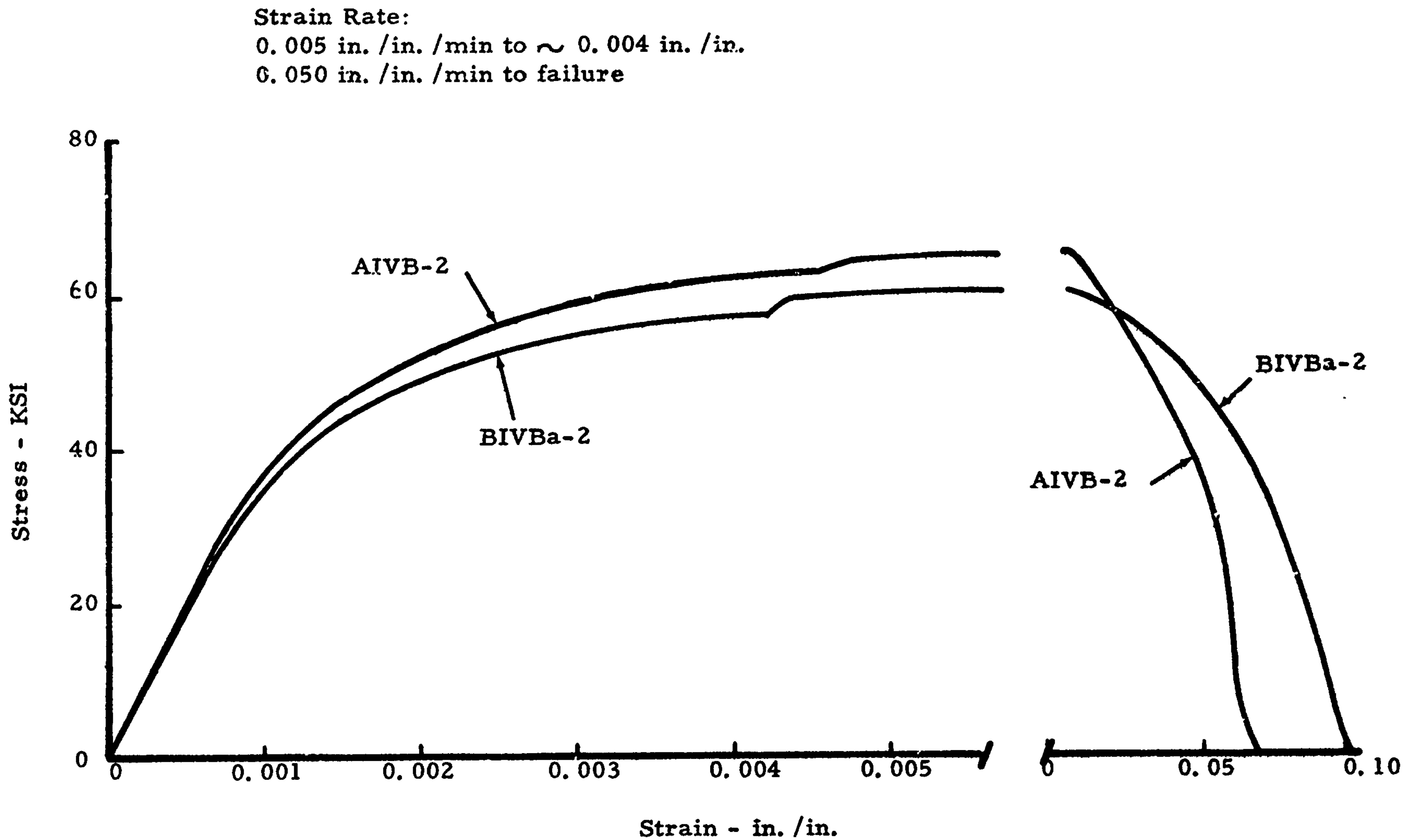


Figure 32. Stress-Strain Curve for Tungsten Bar at 2000°F

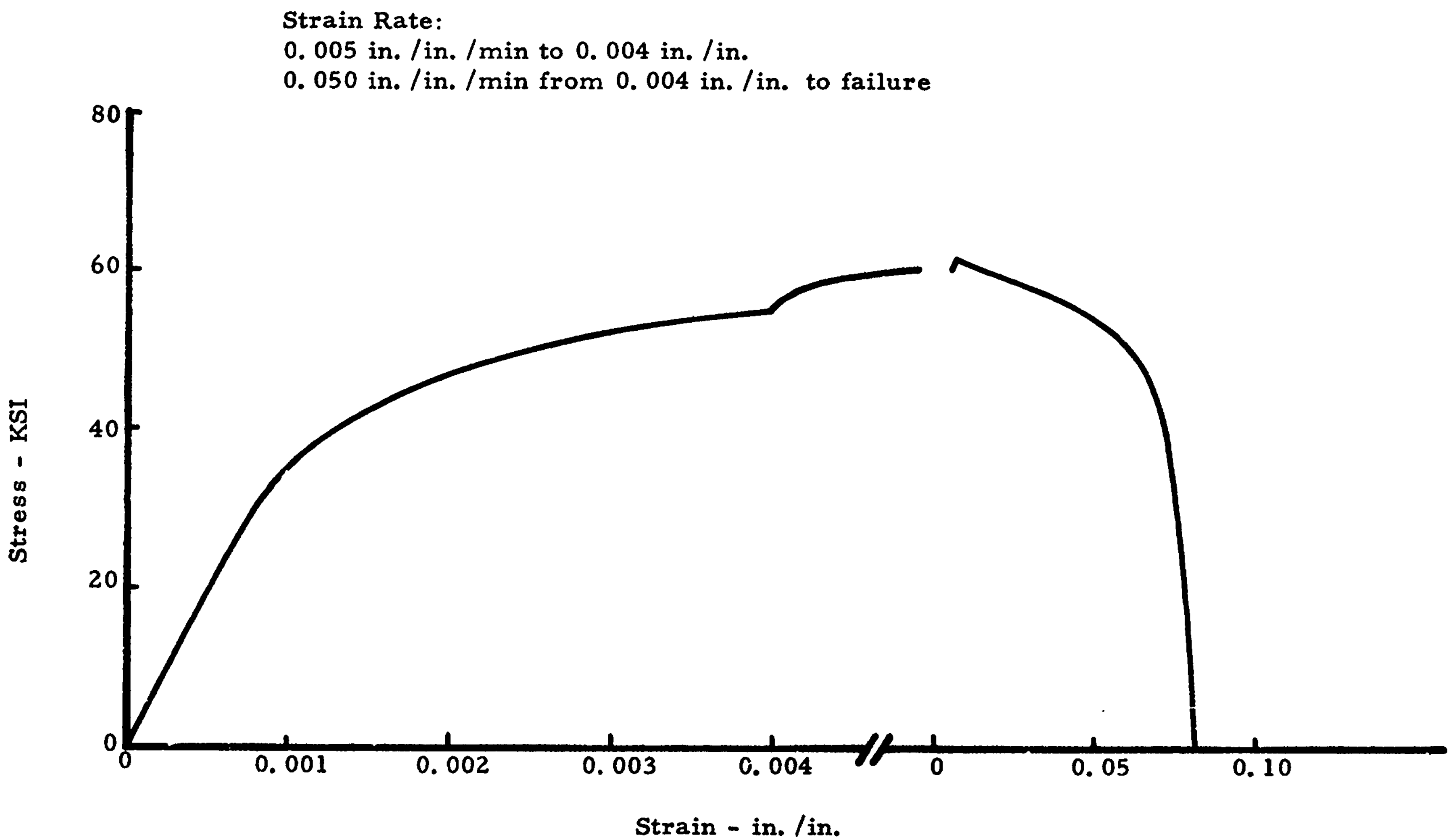


Figure 33. Stress-Strain Curve for Specimen BIIIA-4 at 2000°F

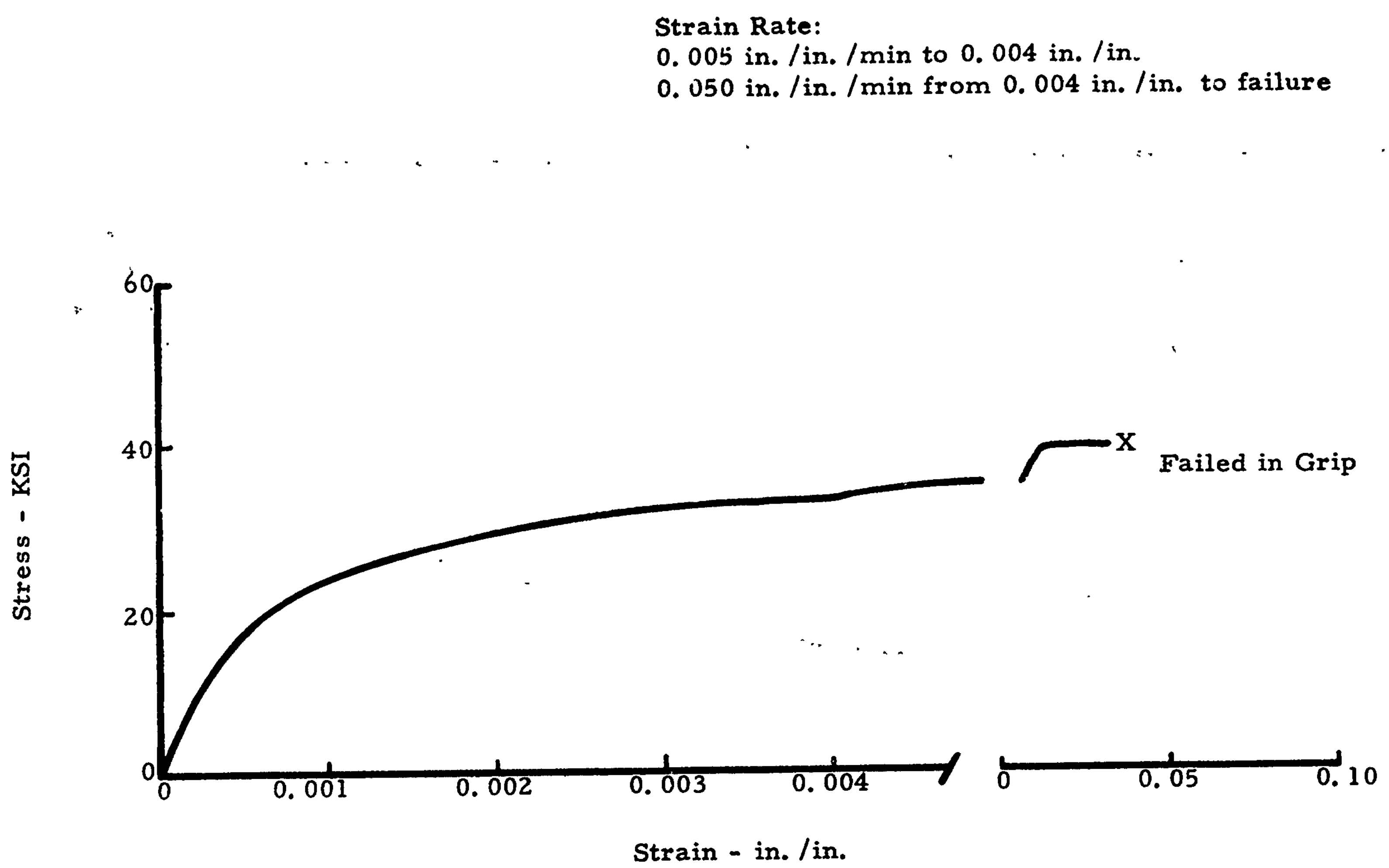


Figure 34. Stress-Strain Curve for Specimen BIIIB-4 at 2000°F

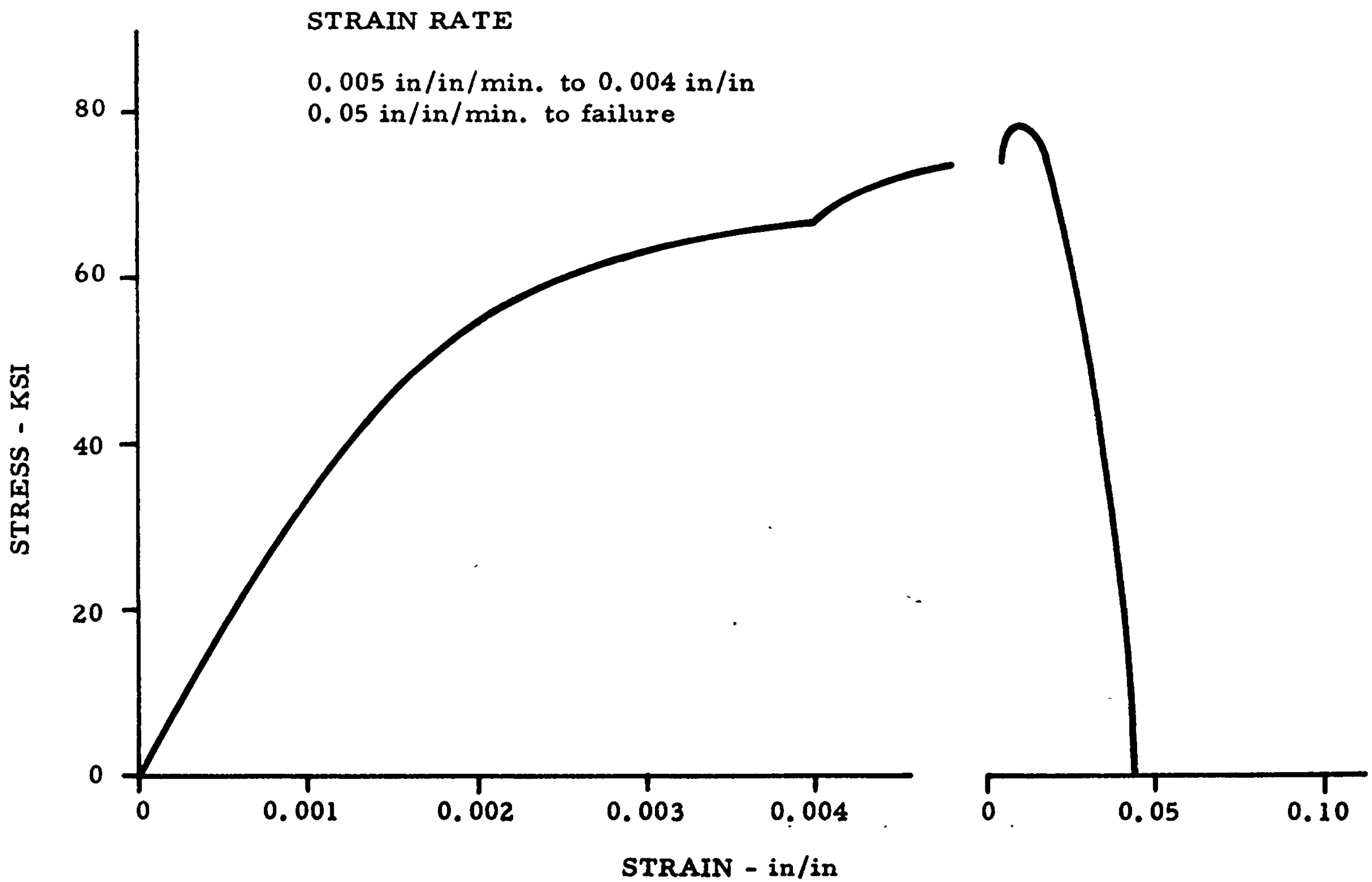


Figure 35. Stress-Strain Curve for CIIIAb-5 at 2000°F

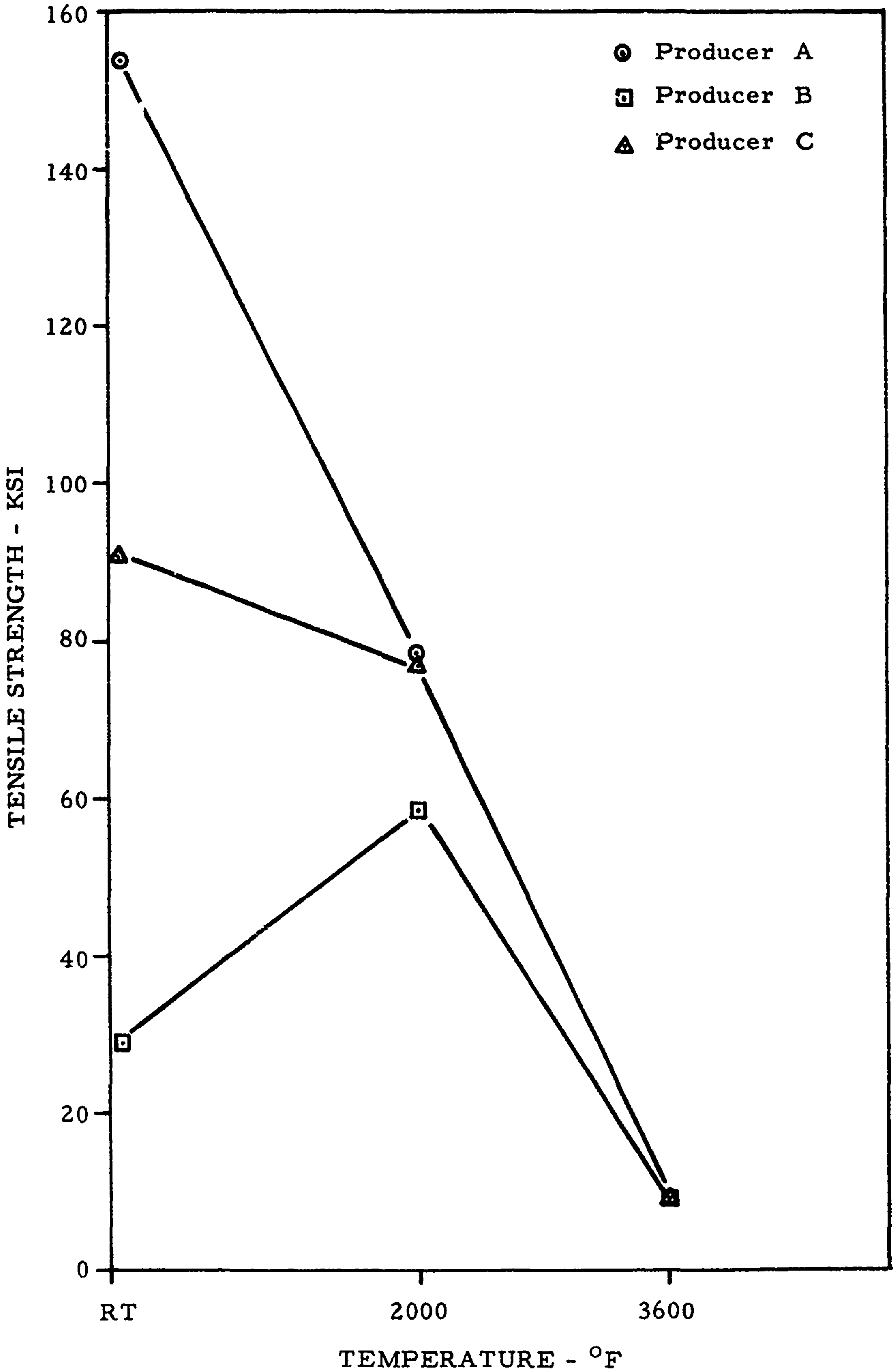


Figure 36. Average Tensile Strength versus Temperature For Tungsten Sheet

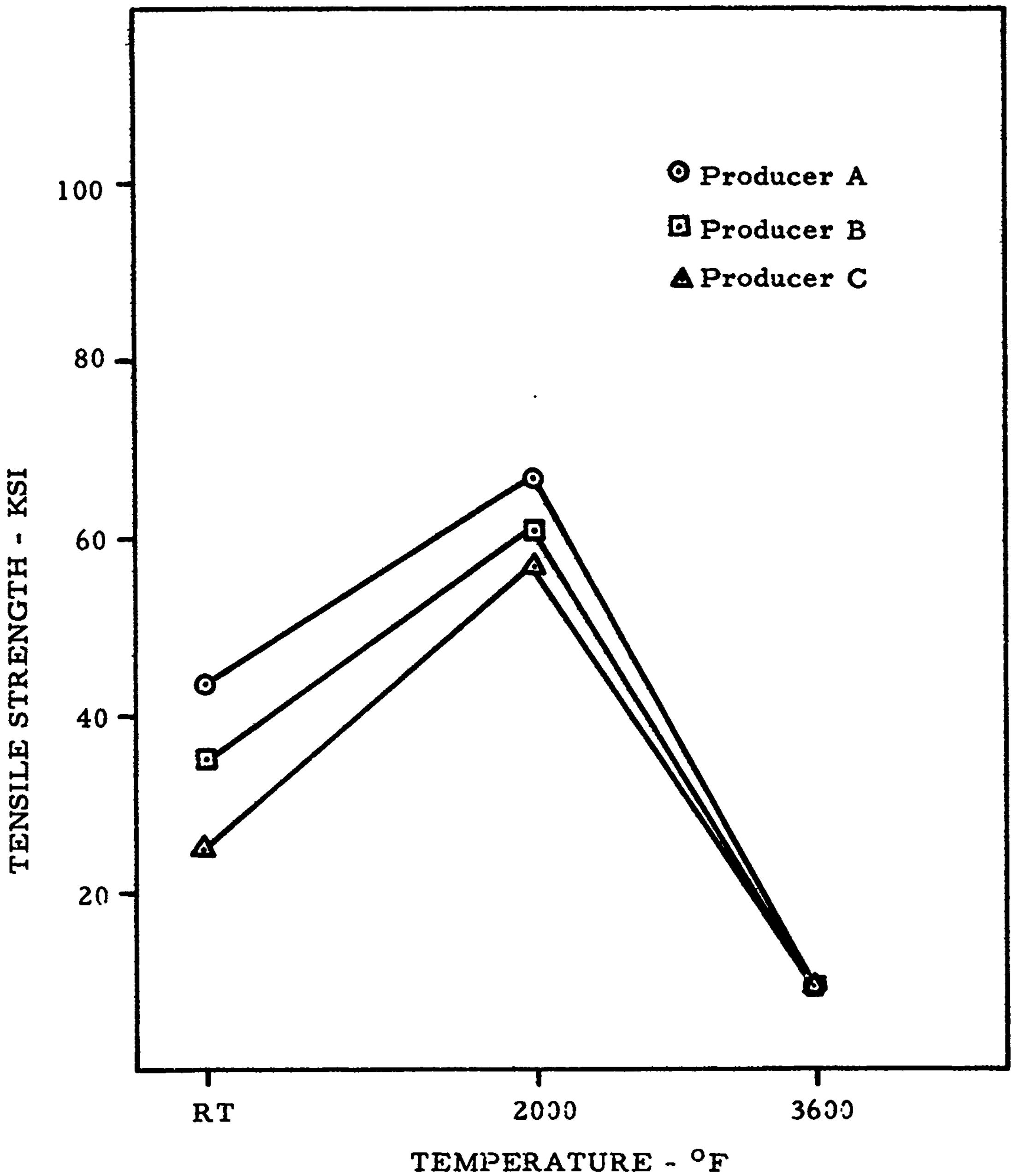


Figure 37. Average Tensile Strength versus Temperature For Tungsten Bar

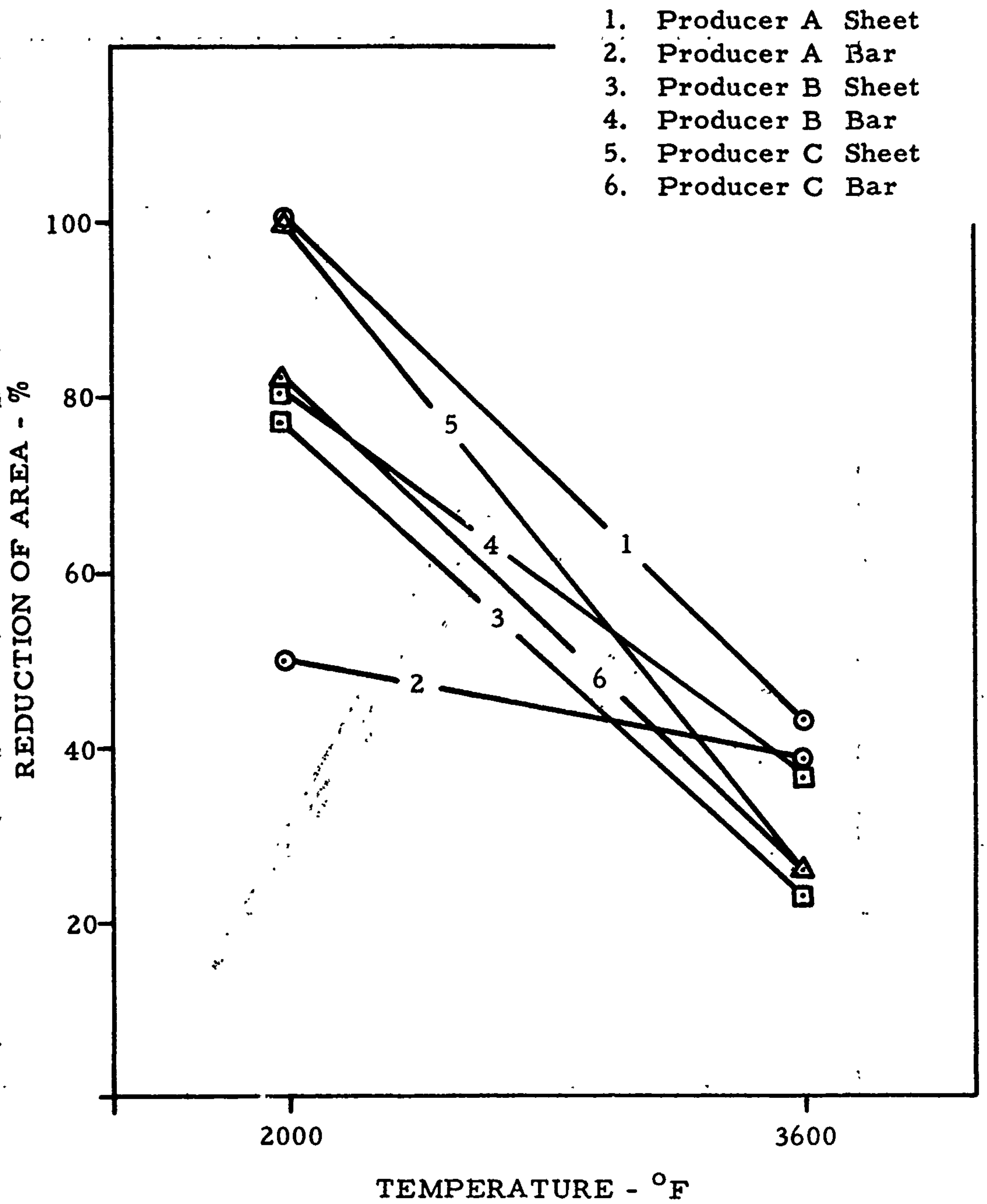


Figure 38. Average Reduction of Area versus Temperature

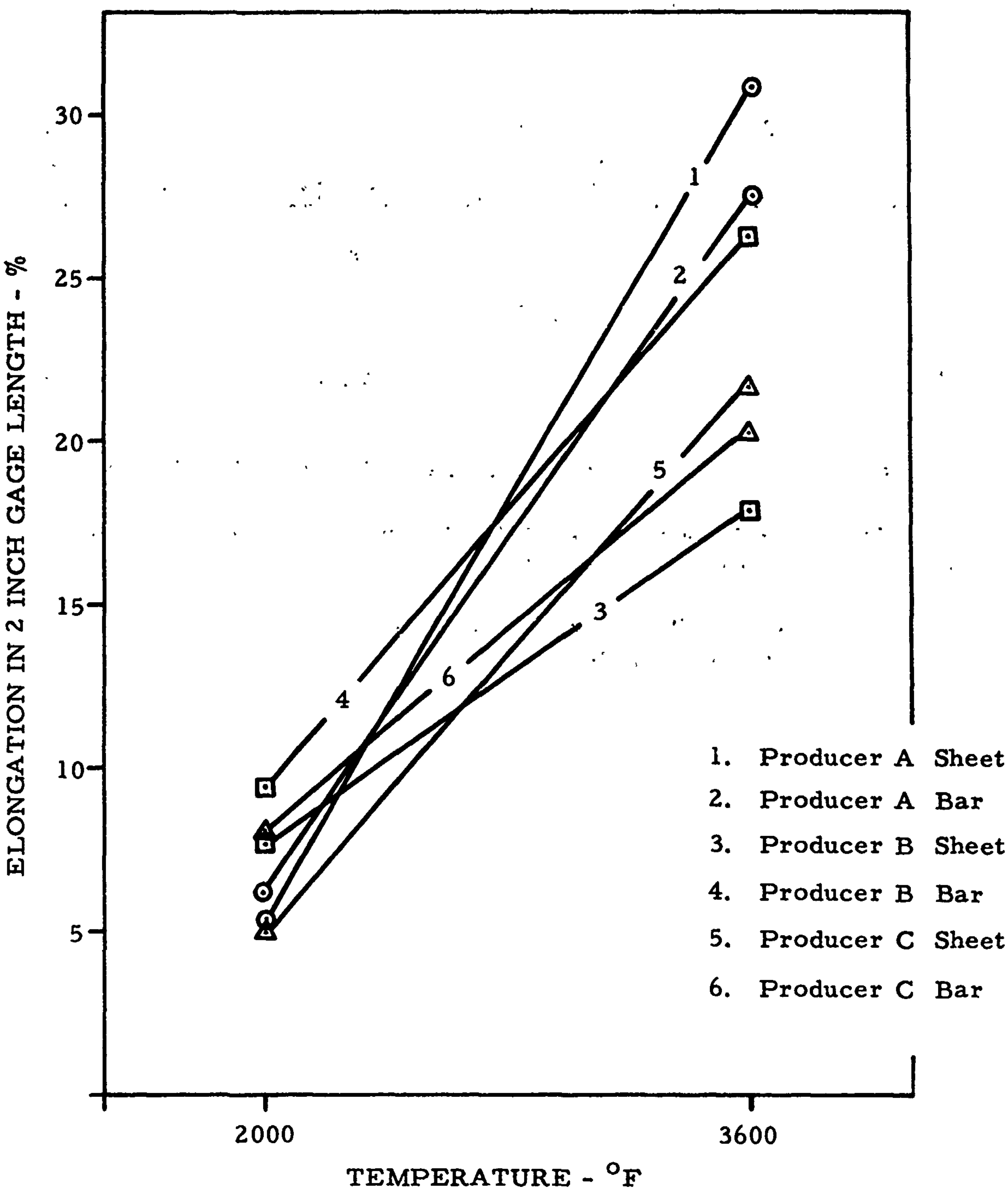


Figure 39. Average Elongation versus Temperature

TABLE XXIV

TENSILE TESTING CONDITIONS
(Except as noted on data tabulations)

Temperature (°F)	Time to Temperature (minutes)	Soak Time at Temperature (minutes)	Atmosphere	Strain Rate (in. /in. /min.) to 0.4% strain	from 0.4% to failure
RT	-		Air	.005	.005
2000	1.5	5.0	Argon	.005	.050
3600	1.0	3.0	Argon	.005	.050

1. Average thermal elongation at 2000°F is 0.53% and at 3600°F is 1.06%
2. Reduction of area values are approximate since the fracture area of the specimens were often difficult to define.
3. A 1% temperature gradient is used in the two inch gage length to insure failure within the gage length.

TABLE XXV

TENSILE TESTS AT ROOM TEMPERATURE OF PRODUCER A TUNGSTEN SHEET

Specimen	U. T. S. (KSI)	Elastic Modulus (PSI x 10^{-6})	Strain Rate (in. /in. /min.)
A I A 10	118.5(2)	48	.06
A I A 15	131.0(2)	58	.06
A I B 12	80.0	53	.005
A I B 18	132.8	48	.005
A I C 1	175.5	55	.05
A I C 4	175.0(3)	60	.005
A II A 10	204.0(5)	47	.06
A II A 15	154.0(2)	50	.06
A II B 18	67.2	46	.005
A II B 19	176.7	43	.005
A II C 1	190.0	42	.05
A II C 4	192.6	49	.005
A III A 10	225.0	47	.06
A III A 15	161.0	45(4)	.06
A III B 11	151.2(5)	57	.005
A III B 18	94.2	47	.005
A III C 2	203.0	49	.005
A III C 5	128.0(6)	47	.005
Ave.	153.3	49	-

Notes:

(1) Specimens AIA-10, AIA-15, AIIA-10, AIIA-15, AIIIA-10, AIIIA-15 were normal type reduced test section tensile specimens, all others were .500 inch constant width specimens.

(2) Failed at radius

(3) Failed at grip

(4) Poor stress-strain curve

(5) Retested after failure at grip

(6) Failure showed evidence of severe delamination to greater extent than indicated by ultrasonic inspection.

TABLE XXVI

TENSILE TESTS AT 2000°F OF PRODUCER A TUNGSTEN SHEET

Specimen	U. T. S. (KSI)	0. 2% Y. S. (KSI)	Elastic Modulus (PSI x 10^{-6})	Elongation %
A I A 16	80. 1	66. 4	25	5. 7
A II A 16	80. 1	64. 8	27	5. 7
A III A 16	81. 4(1)	65. 8	38	-
A I B 13	75. 4	61. 5	53	5. 0
A I B 14	77. 4	61. 9	51	5. 3
A II B 16	76. 6	62. 3	42	4. 7
A II B 17	77. 4	63. 2	42	5. 0
A III B 12	75. 9	62. 7	46	5. 5
A III B 13	70. 1(1)	57. 7	44	-
A I C 2	79. 8(1)	66. 7	25	-
A I C 3	79. 8	67. 7	25	5. 5
A II C 2	78. 7	67. 0	25	4. 4
A II C 3	78. 5	64. 6	27	5. 9
A III C 1	77. 5	62. 3	35	5. 5
A III C 3	77. 8	63. 8	29	5. 5
Ave.	78. 6	64. 3	36	5. 3

Notes:

(1) Power application before argon flow caused light brown oxidation in the gage length and failure occurred outside the gage length.

(2) All specimens necked to a sharp edge.

TABLE XXVII

TENSILE TESTS AT 3600°F OF PRODUCER A TUNGSTEN SHEET

Specimen	U. T. S. (KSI)	0. 2% YS (KSI)	Elongation (%)	Reduction of Area (%)
A I A 17	9. 20	4. 73	11. 7 (1)	-
A I A 18	9. 43	4. 73	36. 9	54
A II A 17	8. 93	5. 27	28. 7	36
A II A 18	9. 46	4. 73	28. 9	38
A III A 17	9. 13	4. 78	39. 2	38
A III A 18	9. 17	4. 71	25. 5	52
A I B 16	8. 87	3. 90	35. 7	40
A I B 17	8. 36	3. 31	35. 0	30
A II B 12	8. 98	4. 41	26. 7	37
A II B 13	8. 73	4. 20	24. 0	46
A III B 16	9. 05	3. 92	30. 2	28
A III B 17	8. 91	4. 04	24. 1	37
A I C 5	9. 37	4. 87	33. 4	38
A I C 6	10. 00	5. 29	32. 3	40
A II C 5	9. 65	5. 00	34. 7	40
A II C 6	9. 92	5. 05	27. 8	35
A III C 4	8. 98	4. 36	27. 2	46
A III C 6	9. 40	4. 50	31. 7	41
Ave.	9. 20	4. 54	30. 8	43

Note:

(1) Failed outside gage length.

TABLE XXVIII

TENSILE TESTS AT ROOM TEMPERATURE OF PRODUCER B TUNGSTEN

Strain rate in two inch gage lengths is 0.005 in./in./min.

Specimen	U.T.S. (KSI)	Elastic Modulus (PSI x 10^{-6})
B I A 2	13.2	-
B I A 5	14.8	-
B II A 4	31.5	39
B II A I	80.0	57
B V A 6	40.0	67
B 1 B(1)	13.3	-
B II B 8	12.0	-
B III B 3	29.5	59
B V B 6(2)	20.4	55
B I C 1(2)	43.9	-
B III C 2(2)	20.6	59
Ave.	29.0	56

Notes:

(1) Specimen too short to use extensometer - strain rate approximate
(2) Failed at grip

TABLE XXIX

TENSILE TESTS AT 2000°F OF PRODUCER B TUNGSTEN SHEET

Specimen	U.T.S. (KSI)	0.2% YS (KSI)	Elastic Modulus (PSI x 10^{-6})	Elongation (%)	Reduction of Area (%)
B II A 3	56.4	49.8	.38	8.6	80
B III A 4	61.0	54.1	39	8.2	80
B III A 7	61.4	54.3	36	9.9	82
B V A 3	59.4	52.9	35	6.8	74
B V A 4	59.8	53.3	36	5.4	65
B V B 1	59.7	53.5	37	5.8	80
B V B 7	55.9	52.8	37	7.1	56
B I C 2	53.4	50.4	32	6.2	100(3)
Ave.	58.4	52.6	36	7.2	77
B III B 4	39.3(1)	29.9	See Figure 34		
B III B 5	36.1(2)	29.8	-	-	-

Notes:

(1) Failed in grip after maximum stress was reached
(2) Failed at grip
(3) Necked down to sharp edge

TABLE XXX

TENSILE TESTS AT 3600°F OF PRODUCER B TUNGSTEN SHEET

Specimen	U.T.S. (KSI)	0.2% YS (KSI)	Elongation (%)	Reduction of Area (%)
B I A 1	8.85	3.98	20.1	22
B I A 6	8.92	4.07	11.5	21
B I C 5	9.20	4.09	20.9	30
B I C 6	9.20	3.99	16.6	30
B II A 1	9.34	4.50	13.7	29
B II A 6	9.00	4.70	11.3	20
B II B 1	9.40	4.24	18.5	22
B II B 2	9.52	4.21	19.0	19
B III A 2	9.37	4.35	24.2	26
B III A 3	9.37	4.18	19.5	26
B III B 1	8.72	3.76	21.9	32
B III B 2	8.82	4.01	22.0	22
B III C 3	9.01	4.34	17.2	19
B III C 6	9.30	4.42	13.0	17
B V A 1	9.59	4.78	18.0	25
B V A 2	9.67	4.78	20.7	23
B V B 2	9.58	4.30	15.7	20
B V B 3	9.63	4.33	16.3	20
Ave.	9.25	4.28	17.9	23.4

TABLE XXXI

TENSILE TESTS AT ROOM TEMPERATURE OF PRODUCER C

TUNGSTEN SHEET

Specimen	U. T. S. (KSI)	Elastic Modulus (PSI x 10^{-6})
C I A a-3	98.9	45
C I A a-4	98.5	45
C II A a-3	90.2	47
C II A a-4	87.9	48
C III A b-2	99.6	48
C III A b-3	127.3	47
C I B a-2	60.9	51
C I B a-3	92.6	50
C II B a-2	63.4	-
C II B a-3	82.8	46
C III B a-4	143.0	48
C III B a-5	131.0	49
C I C b-4	73.5	56
C I C b-5	61.4	48
C II C a-2	75.2	44
C II C a-5	36.5	43
C III C a-3	93.9	43
C III C a-2	117.8	44
Ave.	90.8	47
C III C b-2	16.7	-
C III C b-3	18.8	-

TABLE XXXII

TENSILE TESTS AT 2000°F OF PRODUCER C

TUNGSTEN SHEET

Specimen	U. T. S. (KSI)	0. 2% (KSI)	Elastic Modulus (PSI x 10^{-6})	Elongation %
C I A a-2	74. 0	65. 5	35	5. 2
C I A a-5	76. 4	64. 9	36	4. 5
C II A a-2	77. 1	65. 0	32	5. 0
C II A a-5	73. 7	64. 6	32	5. 9
C III A b-4	80. 1	67. 2	34	4. 7
C III A b-5	78. 1	66. 3	36	4. 5
C I B a-4	77. 7	66. 7	41	5. 1
C I B a-5	76. 9	66. 8	41	5. 5
C II B a-4	75. 7	65. 3	34	5. 0
C II B a-5	75. 9	65. 4	37	4. 7
C III B a-2	81. 5	67. 6	32	5. 7
C III B a-3	80. 8	67. 1	32	5. 3
C I C b-2	75. 9	65. 0	32	4. 7
C I C b-3	76. 0	65. 7	31	4. 8
C II C a-3	(1)	65. 4	35	-
C II C a-4	75. 7	65. 4	36	5. 4
C III C b-1	(1)	-	31	-
C III C b-5	77. 3	67. 1	32	4. 3
Ave.	77. 0	65. 9	34	5. 0

Notes:

(1) Failed at grip

(2) All specimens necked to sharp edge

TABLE XXXIII

TENSILE TESTS AT 3600°F OF PRODUCER C

TUNGSTEN SHEET

Specimen	U. T. S. (KSI)	0.2% YS (KSI)	Elongation (%)	Reduction of Area (%)
C I A a-1	9.51	4.92	14.7	20
C I A a-6	9.25	5.09	22.7	23
C II A a-1	9.12	4.56	25.2	24
C II A a-6	9.40	4.91	22.9	25
C III A b-1	9.58	5.19	23.0	23
C III A b-6	9.25	4.98	19.2	26
C I B a-1	9.47	4.74	24.9	28
C I B a-6	9.34	4.84	25.0	26
C II B a-1	8.94	4.68	17.8	26
C II B a-6	8.92	4.58	24.5	26
C III B a-1	8.97	5.12	22.1	28
C III B a-6	9.11	5.09	24.7	29
C I C b-1	9.18	4.63	19.1	26
C I C b-6	9.58	5.09	22.2	23
C II C a-1	9.28	4.96	15.7(1)	26
C II C a-6	9.48	4.91	20.1	26
C III C a-1	9.16	4.92	18.5	31
C III C b-6	9.32	5.13	20.3	29
Ave.	9.27	4.91	21.6	25.8

(1) Necking occurred at extensometer point.

TABLE XXXIV

TENSILE TESTS OF TUNGSTEN BAR AT ROOM TEMPERATURE

Specimen	U.T.S. (KSI)	Elastic Modulus (PSI x 10^{-6})
A IV B 5	37.2	57
A IV C 3	49.8	50
B IV B a-6	66.3	70
B IV B a-4	34.7	53
B IV 3 a-4	45.7	54
B IV 3 a-5	66.1	70
B IV 4 a-1	38.0 (1)	-
C IV A b-1	26.3 (1)	-
C IV A b-2	26.2	-
C IV C c-2	26.8	54
C IV C c-5	18.3	-
C IV B a-1	28.2	63

(1) Failed at grip

TABLE XXXV

TENSILE TESTS OF TUNGSTEN BAR AT 2000°F

Specimen	U. T. S. (KSI)	0. 2% YS (KSI)	Elastic Modulus (PSI x 10^{-6})	Elongation (%)	R A (%)
A IV B-2	67. 2	61. 2	39	6. 3	50
A IV B-4	56. 3(3)	-	40	-	-
A IV C-5	74. 1	60. 3	37	9. 2	84
B IV B a-2	60. 5	55. 4	40	9. 7	80
B IV B a-3	61. 0	54. 5	40	9. 4	80
B IV 3 a-6	68. 4	60. 6	39	8. 0	62
B IV 3 a-1	61. 9(3)	-	-	-	-
B IV 4 a -1	68. 4	60. 8	34	9. 4	62
B IV 4 a-6	55. 1(3)	-	40	-	-
C IV A b-3	57. 3	53. 8	32	8. 1	81
C IV A b-1	50. 2(1)	49. 8	39	-	-
C IV B a-2	32. 4(1)	-	38	-	-
C IV C c-3	33. 2(1)	-	-	-	-
C IV C c-4	41. 4(1)	44. 0(2)	41	—	—

(1) Failed outside 2000°F test area

(2) Extrapolated

(3) Failed in grip

TABLE XXXVI

TENSILE TESTS OF TUNGSTEN BAR AT 3600°F

Specimen	U. T. S. (KSI)	0. 2% YS (KSI)	Elongation (%)	R A (%)
A IV B 1	9. 01[1]	3. 59	23. 8	32
A IV B 3	9. 87	4. 04	26. 8	37
A IV C 2	9. 34	4. 10	30. 0	43
A IV C 4	9. 23	4. 18	29. 1	45
B IV B a-1	9. 52	4. 40	30. 9	35
B IV B a-5	9. 76	4. 56	27. 5	39
B IV 3 a-2	9. 77	4. 64	23. 7	37
B IV 3 a-3	9. 88	4. 68	26. 0	31
B IV 4 a-4	10. 04	4. 80	24. 2	31
B IV 4 a-5	9. 85	4. 82	25. 2	31
C IV A b-4	9. 86	4. 58	21. 9	24
C IV A b-6	9. 33	4. 33	15. 0	23
C IV B a-3	9. 13	4. 04	23. 6	25
C IV B a-4	9. 49	4. 29	19. 2	27
C IV C c-1	9. 26	4. 09	21. 3	33
C IV C c-6	9. 51	4. 62	20. 2	23

(1) Soaked at temperature about 30 minutes.

TABLE XXXVII

AVERAGE TENSILE STRENGTHS OF PRODUCER A TUNGSTEN SHEET AT ROOM TEMPERATURE

Strengths shown are KSI

	Powder Lot			Average of Lots A, B, C
	A	B	C	
I 20% cold reduction 1850°F Stress Relief	124.8	106.4	175.3	135.5
II 20% cold reduction as-rolled	179.0	122.0	191.3	164.1
III 50% cold reduction 1850°F Stress Relief	193.0	122.7	165.5	160.4
Average of Groups I, II, III	165.6	117.0	177.4	153.3

TABLE XXXVIII

AVERAGE TENSILE STRENGTHS OF PRODUCER A TUNGSTEN SHEET AT 2000°F

Strengths shown are KSI

	Powder Lots			Average of Lots A, B, C
	A	B	C	
I 20% cold reduction 1850°F Stress Relief	80.1	76.4	79.8	78.8
II 20% cold reduction as-rolled	80.1	77.0	78.6	78.6
III 50% cold reduction 1850°F Stress Relief	81.4	75.9	77.7	78.3
Average of Groups I, II, III	80.5	76.4	78.7	78.6

TABLE XXXIX

AVERAGE TENSILE STRENGTHS OF PRODUCER A TUNGSTEN SHEET AT 3600°F

Strengths shown are KSI

	Powder Lot			Average of Lots A, B, C
	A	B	C	
I 20% cold reduction 1850°F stress relief	9.31	8.62	9.69	9.22
II 20% cold reduction as-rolled	9.26	8.86	9.79	9.28
III 50% cold reduction 1850°F stress relief	9.15	8.98	9.19	9.11
Average of Groups I, II, III	9.22	8.82	9.55	9.20

TABLE XL

AVERAGE TENSILE STRENGTHS OF PRODUCER B TUNGSTEN SHEET AT 3600°F

Strengths shown are KSI

	Powder Lot		
	A	B	C
I 30% cold reduction 2460°F stress relief	8.88		9.20
II 30% cold reduction as-rolled	9.17	9.46	
III 60% cold reduction 2460°F stress relief	9.37	8.77	9.16
V 90% cold reduction 2460°F stress relief	9.63	9.61	

TABLE XLI

AVERAGE TENSILE STRENGTHS OF PRODUCER C TUNGSTEN SHEET AT ROOM TEMPERATURE

Strengths shown are KSI

	Powder Lot			Average of Lots A, B, C
	A	B	C	
I 67% cold reduction 1650°F stress relief	98.7	76.8	67.5	81.0
II 67% cold reduction as-rolled	89.1	73.1	55.9	72.7
III 80% cold reduction 1650°F stress relief	113.5	137.0	105.9(1)	118.8
Average of Groups I, II, III	100.4	95.6	76.4	90.8

(1) Sheet CIIICa, sheet CIIICb results not included

TABLE XLII

AVERAGE TENSILE STRENGTHS OF PRODUCER C TUNGSTEN SHEET AT 2000°F

Strengths shown are KSI

	Powder Lot			Average of Lots A, B, C
	A	B	C	
I 67% cold reduction 1650°F stress relief	75.2	77.3	76.0	76.2
II 67% cold reduction as-rolled	75.4	75.8	75.7	75.6
III 80% cold reduction 1650°F stress relief	79.1	81.2	77.3	79.2
Average of Groups I, II, III	76.6	78.1	76.3	77.0

TABLE XLIII

AVERAGE TENSILE STRENGTHS OF PRODUCER C TUNGSTEN SHEET AT 3600°F

Strengths shown are KSI

	Powder Lot			Average of Lots A, B, C
	A	B	C	
I 67% cold reduction 1650°F stress relief	9.38	9.41	9.38	9.39
II 67% cold reduction as-rolled	9.26	8.93	9.38	9.19
III 80% cold reduction 1650°F stress relief	9.42	9.04	9.24	9.23
Average of Groups I, II III	9.35	9.13	9.33	9.27

TABLE XLIV

SUMMARY OF AVERAGE VALUES FOR TUNGSTEN

TENSILE TESTS

		Temperature (°F)	U. T. S. (KSI)	0.2% YS (KSI)	Elongation (%)	Reduction of Area (%)	Elastic Modulus (PSI x 10^{-6})
Producer A	Sheet	RT	153.3	-	-	-	49
		2000	78.6	64.3	5.3	100	36
		3600	9.20	4.54	30.8	43	-
	Bar	RT	43.5	-	-	-	53
		2000	67.2	61.2	6.3	50	39
		3600	9.36	3.98	27.4	39	-
Producer B	Sheet	RT	29.0	-	-	-	56
		2000	58.4	52.6	7.2	77	36
		3600	9.25	4.28	17.9	23	-
	Bar	RT	34.7	-	-	-	53
		2000	60.7	55.0	9.5	80	40
		3600	9.80	4.65	26.2	34	-
Producer C	Sheet	RT	90.8	-	-	-	47
		2000	77.0	65.9	5.0	100	34
		3600	9.27	4.91	21.6	26	-
	Bar	RT	25.1	-	-	-	58
		2000	57.3	49.2	8.1	81	37
		3600	9.43	4.32	20.2	26	-

SUMMARY

Tables XLV through XLVIII are summaries of the important data used in formulating HMS 6-1066, (Appendix A), the specification for high strength, high quality tungsten sheet. The intent of the tungsten sheet specification HMS 6-1066 is to require a minimum cold reduction level of "3", as shown in Table XLV, and that no stress relief shall be used.

Table XLV shows a summary of the average mechanical properties of the tungsten sheet. The values are the averages of three powder lots. This tabulation shows the variation of strength, with degree of cold work and the stress relief treatment. The cold reduction levels were assigned arbitrarily, based on microstructure and information supplied by the producer. All three producers' 0.250-inch thick bar ranged near the lowest cold reduction level.

At low temperatures, strength differences due to powder lots, were small compared to cold reduction and stress relief treatments. Stress relieving at 1832°F caused an average reduction of room temperature tensile strength from 164,000 psi to 135,500 psi; and a similar decrease of the flexure strength. Stress relieving at 1650°F caused an average increase of room temperature tensile strength from 72,700 psi to 81,000 psi, although the flexure strength decreased from 123,000 psi to 109,000 psi. Stress relieving at 2460°F caused recrystallization with an average room temperature tensile strength level of 29,000 psi. Cold reduction level and stress relief did not affect the tensile strength at 3600°F. The minimum and maximum tensile strengths for a total of 70 sheet and bar specimens from nine (9) powder lots which were tested at 3600°F was 8,360 psi and 10,040 psi respectively.

A summary of the average mechanical properties of tungsten sheet versus the starting powder lot is shown in Table 2. These values are averages of all fabrication conditions of identical powder lots. Oxygen content appears to be the most significant impurity showing any correlation with strength variation. A complete summary of chemical and semi-quantitative spectrographic analysis are presented in Tables 3 and 4.

The tendency of some of this material to delaminate, which was observed with both ultrasonic inspection and bend angle tests, may correspond to purity. The most serious delaminations were found in the Producer A powder lot B material which also had the highest oxygen and hydrogen levels. The test results in Part III of this report did not show any delamination difficulties for Part III materials which had equivalent or greater cold work and higher purity levels than these Part II materials.

TABLE XLV

SUMMARY OF AVERAGE MECHANICAL PROPERTIES OF TUNGSTEN SHEET IN COMPARISON WITH COLD REDUCTION LEVEL

Tensile Strength at R. T. (KSI)	Rupture Modulus at R. T. (KSI)	Bend Angle at 300°F	Tensile Strength at 2000°F (KSI)	Tensile Strength at 3600°F (KSI)	Producer	Cold Reduction Level (a)	Stress Relief (°F)
29.0	89	$<4^\circ$	58.4	9.25	B	1 (lowest)	2460
72.7	123	$<4^\circ$	75.6	9.19	C	2	none
81.0	109	$<4^\circ$	76.2	9.39	C	2	1650
118.8	180	9°	79.2	9.23	C	3	1650
135.5	241	93°	78.8	9.22	A	4	1832
160.4	332	80°	78.3	9.11	A	5 (highest)	1832
164.1	278	103°	78.6	9.28	A	4	none

(a) Cold reduction values assigned by inspection of microstructure and the information supplied by the producers.

TABLE XLVI

SUMMARY OF AVERAGE MECHANICAL PROPERTIES OF TUNGSTEN SHEET IN COMPARISON TO POWDER LOT

Producer	Powder Lot	Tensile Strength at R.T. (KSI)	Rupture Modulus at R.T. (KSI)	Bend Angle at 300°F	Tensile Strength at 2000°F (KSI)	Tensile Strength at 3600°F (KSI)	Oxygen (PPM)
C	C	76.4	135.6	-	76.3	9.33	21
C	B	95.6	144.5	-	78.1	9.13	45
C	A	100.4	130.9	-	76.6	9.35	28
A	B	117.0	283	76	76.4	8.82	- 140
A	A	165.6	290	126	80.5	9.22	82 - 98
A	C	177.4	278	76	78.7	9.55	38

TABLE XLVII

SUMMARY OF CHEMICAL AND SEMI-QUANTITATIVE ANALYSES

SPECIMEN	COMPOSITION, PPM BY WEIGHT						
	O_2 (a)	H_2 (a)	N_2 (b)	C (c)	Mo (d)	Fe (d)	Zr (d)
A I A -2	98	9	17	-	50-500	P - 100	10-50
A II A -2	82	7	17	-	50-500	P - 100	10-50
A III A -5	91	7	15	-	50-500	P - 100	10-50
A II B -18	140	10	2	30	10-100	P - 100	P - 10
A III B -4	81	3	21	40	20-200	P - 100	10-50
A I C -4	38	4	3	30	10-100	P - 100	P - 10
B I A -2	52	8	8	30	P - 10	100-1000	P - 10
B V B -6	42	3	10	20	10-100	50-500	P - 10
B III C -2	66	5	13	20	10-100	50-500	P - 10
C I A a-1	28	1	8	P - 5	100-1000	100-300	P - 10
C II B a-3	45	P-1	8	P - 5	50-300	100-300	P - 10
C II C a-2	21	2	15	P - 5	50-300	100-300	P - 10

P - present but less than amount indicated

(a) Vacuum fusion analysis

(b) Micro-Kjeldahl analysis

(c) Conductometric analysis

(d) Semi-quantitative spectrographic analysis

TABLE XLVIII

SEMI-QUANTITATIVE SPECTROGRAPHIC ANALYSES FOR ALL SPECIMENS SHOWN IN TABLE XLVII

P - present but less than amount indicated

ND - not detected

Element	PPM by Weight
Si	P - 100
Al	P - 100
Ti	P - 10
Cu	P - 10
Ni	P - 10
Cr	P - 100
V	P - 100
Mn	P - 10
Ca	P - 100
mg	P - 10
Bi	P - 100
Pb	P - 50
Sn	P - 100
Ag	ND
Co	P - 10
Sb	ND
As	ND
B	ND
Zn	P - 100
Na	P - 100
Li	P - 100
Cd	ND

PART III

DETERMINATION OF THE TENSILE PROPERTIES OF TUNGSTEN SHEET PROCURED FROM FIVE SOURCES

INTRODUCTION

The purpose of this phase of testing was to determine the tensile properties of material procured from five producers to the Hughes Tool Company -- Aircraft Division specification HMS 6-1066, a result of the Part II Quality Control Evaluation. Tensile test results for three powder lots from each of five producers are presented for room temperature, 1000°, 2000°, 3600° and 4400°F. Plastic elongation up to 1.5% was displayed at room temperature. Correlation between room temperature hardness and tensile strength is shown.

DISCUSSION

Requests for quotation for three powder lots of tungsten sheet per HMS 6-1066 (Appendix A) were sent to sixteen organizations. Bids were received from seven and orders were placed with five. One of these orders was cancelled because the producers' tungsten rolling program was not sufficiently advanced to supply sheet conforming to the specifications. One producer with whom no order was placed voluntarily submitted material for evaluation. These orders were for a total of six sheets of tungsten, 0.050" x 3" x 11", comprised of two sheets of each of three powder lots.

Tensile test specimens were 0.500" constant width strip specimens with the grain in the longitudinal direction. This procedure simplifies fabrication, reduces the quantity of material required and enables adjustment of the heated length of the specimen for achieving the minimum practical thermal gradient at all temperatures.

Temperatures for tensile tests for this producer survey phase of testing were room temperature, 1000°, 2000°, 3600° and 4400°F.

For tensile tests at 1000°F, temperature was measured with .005" diameter chromel-alumel thermocouples. Temperature measurement at 2000°, 3600° and 4400°F was accomplished with two color optical pyrometers (Shawmeter Models SMP1 and SMP3). All temperatures are reported as true temperatures. Pyrometer readings were corrected to true temperature, based on the values of emissivity reported in DMIC Report 127, "Physical and Mechanical Properties of Tungsten and Tungsten-Base Alloys".

Table XLIX gives a summary of the tensile testing conditions. The $50^{o}F$ temperature gradient at 1000^{o} was the minimum that could be achieved with a specimen length of 11 inches. At 2000^{o}, 3600^{o} and $4400^{o}F$ the specimen length between the water cooled grips was chosen to give the gradients shown in Table XLIX. These gradients are required to prevent failure outside the extensometer gage length.

The temperature gradient across a tungsten sheet specimen with a center temperature of $1000^{o}F$ was determined and is shown in Figure 40. The non-symmetry of temperature for this particular specimen may be caused by small differences in cross sectional area of the tungsten specimen. Chromel-Alumel thermocouples of .005" diameter were spot welded to the tungsten for temperature determination. The constant cross section specimen was resistance heated over the entire 6.50" length between grips. The grips remained very close to room temperature.

Warpage checks, surface finish checks and ultrasonic testing for internal defects were conducted on the Producer A, B, C, E and F tungsten and all the material fell within the specifications for these conditions. The Producer E tungsten was characterized by very large grain size. The surface of this material had a "galvanized" appearance.

A description of the specimen numbering system appears in Table L. Producers A, B and C are the same producers as A, B and C producers in Part II. It should be noted that the powder lot coding A, B and C do not indicate that each producer used the same three powders of material nor do they relate to the Part II powder lots.

Complete tabulation of the tensile test results on Producers' A, B, C, E and F tungsten are presented in Tables LI thru LV. The full complement of tensile tests were not conducted on the Producer E material as it had low tensile strength and did not meet the requirements of HMS 6-1066 (grain structure).

Review of the tabulated test data shows that four of the five producers supplied at least one sheet of tungsten which exhibited plastic elongation at room temperature. Specimens taken from all six sheets supplied by Producer B exhibited plastic elongation from 0.11 to 1.52%.

Figures 41 and 42 show the stress-strain curves for a single sheet of Producer B tungsten from room temperature to $4400^{o}F$. The waviness of the curves in the elastic region is believed to be caused by the inaccuracies of the high temperature extensometer. The jagged curves shown in Figure 42 are believed to be caused by small frictional forces existing in the loading train.

A summary of the average tensile test results broken down by producer is shown in Table LVI.

Ultimate tensile strength versus temperature is shown in Figure 43. It is noted that the strength variation is consistent with the source of the material for room temperature to 2000°F. At these temperatures the Producer B material has the highest strength followed by A, F, C and E in decreasing order. The data were not graphed for Producer E at room temperature because of large scatter of the individual tests. All room temperature values obtained for Producer E are below the 1000°F strength.

The Producer B tungsten is 45% stronger than Producer E material at 1000°F and 2000°F. At 3600°F the maximum differences in strength between the five producers is less than 12% and at 4400°F the difference increases to 36%. The producer E material shows the highest strength at both 3600°F and 4400°F.

The 0.2% yield stress versus temperature is shown in Figure 44. It is important to note that only the Producer B material consistently exhibited a room temperature yield stress. The yield strengths at 1000°F and 2000°F follow the trend of the ultimate strengths. Producer B and E materials exhibit the highest yield strengths at 3600°F and 4400°F. At 4400°F the highest yield stress material, Producer E, is 68% above the lowest, Producer A.

Producers A and F material had the best ductility at all test temperatures except room temperature. This is clearly shown in Figure 45 of Elongation versus Temperature and Figure 46 of Reduction of Area versus Temperature. In comparison with the other four producers, Producer B material showed intermediate ductility except at room temperature - where it was significantly better than the other four.

Elastic modulus versus temperature is shown in Figure 47. This graph indicates that different modulus values exist for the different producers' materials. All these values were determined with the water cooled high temperature extensometer. At room temperature the accuracy of the elastic modulus is within plus or minus 10% of the true value. This accuracy deteriorates as the elastic strain decreases with increasing temperature. At 4400°F, where the elastic strain is in the order of .0001 in/in, the accuracy of the elastic modulus is approximately within plus or minus 35%. In many cases the load-strain curves at 4400°F are not of sufficient quality to determine the elastic modulus. The lag of the extensometer in picking up the initial strain causes this problem.

A combination of the plus or minus .0001 in/in non-linearity, the existence of a primary and secondary elastic modulus and an occasional large lag in initial strain pickup caused difficulty in interpreting the stress-strain curves generated with the water cooled high temperature extensometer.

Much of the scatter of the modulus data may be attributed to these causes. The modulus values determined represent the straight line average of the stress-strain curve from zero strain to the strain at the best estimate of the proportional limit.

It was decided that it would be advisable to conduct room temperature tensile tests with high accuracy strain measurement. For this purpose a 5000 pound Emery-Baldwin Tate testing machine with a conventional room temperature extensometer utilizing a Peters Microformer was used to determine the stress-strain relationship of tungsten. This extensometer has a strain measuring accuracy within plus or minus 20 micro in/in. The modulus of elasticity was determined for five specimens which had not been previously loaded. Each specimen was loaded and unloaded to about one-half of its ultimate strength. From three to five consecutive loadings were used for each specimen. The modulus values from these tests are shown in Table LVII. The curves for the first loading of the specimens are shown in Figure 48. The results show that on the initial loading a primary and secondary modulus exists. Specimen AIC-9 from Phase I showed the transition from the primary to the secondary modulus to exist at 35,000 psi. For AC-1, BA-6 and CA-5 the transition occurred at 50,000 to 55,000 psi. A double modulus was not found for specimen FB-5 which was loaded to a maximum stress of 66,000 psi. On the second and succeeding loadings the stress-strain relationship changed significantly as indicated by the change of modulus shown in Table IX. The strain rate used on these tests was .001 to .004 in/in/min.

Rockwell 45-N hardness values taken at the center of each tungsten sheet are shown in Table LVIII. A summary of the averages of all the room temperature strength and hardness tests conducted on both phases of this program are presented in Table LIX. The averages are broken down by phase and producer, and are graphed in Figure 49 to show the relation between strength and hardness.

The chemical and spectrographic analyses of Producer A, B, C, F and E materials are presented in Table LX and LXI. Attempts to find a correlation between impurity level and strength or ductility were not successful.

The microstructure of the as-received material is shown in Figure 50. The hardness and tensile strength for the tungsten sheet from which the metallographic specimen was taken, is given beneath the photographs. It is seen that a fine elongated grain structure exhibits the highest hardness level and highest tensile strength.

The microstructure of tungsten at the fracture after tensile testing at 4400°F is shown in Figure 51. The Producer B material showed the most homogeneous and smallest recrystallized grain structure, which is consistent with its high strength at this temperature. Producer A and F material

exhibited the largest grain size which correlates with these materials having lower strength and higher ductility at this temperature.

In conclusion, it is seen that large differences in ultimate strength and yield strength exist for the different producer's material at all temperatures. The difference at room temperature, 1000°F and 2000°F are most likely due to fabrication variables, such as sintering temperatures and rolling temperatures and reduction schedules. The differences at 3600°F and 4400°F are most possibly due to impurities. The impurities which affected strength or ductility could not be determined from the available chemical analyses.

TABLE XLIX

TENSILE TEST CONDITIONS

Extensometer gage length is 2.0 inches.
Self resistance heating.

True Temperature (°F) Center	1" from Center	Time to Temperature (Minutes)	Hold Time (Minutes)	Atmosphere	Strain Rate (in/in/min) .2% YS	UTS
RT	RT	--	--	Air	.005	:005
1000	950	~1.0	5.0	Argon	.005	.05
2000	1985	~1.0	5.0	Argon	.005	.05
3600	3570	~1.0	3.0	Argon	.005	.05
4400	4330	~0.5	3.0	Argon	.005	.05

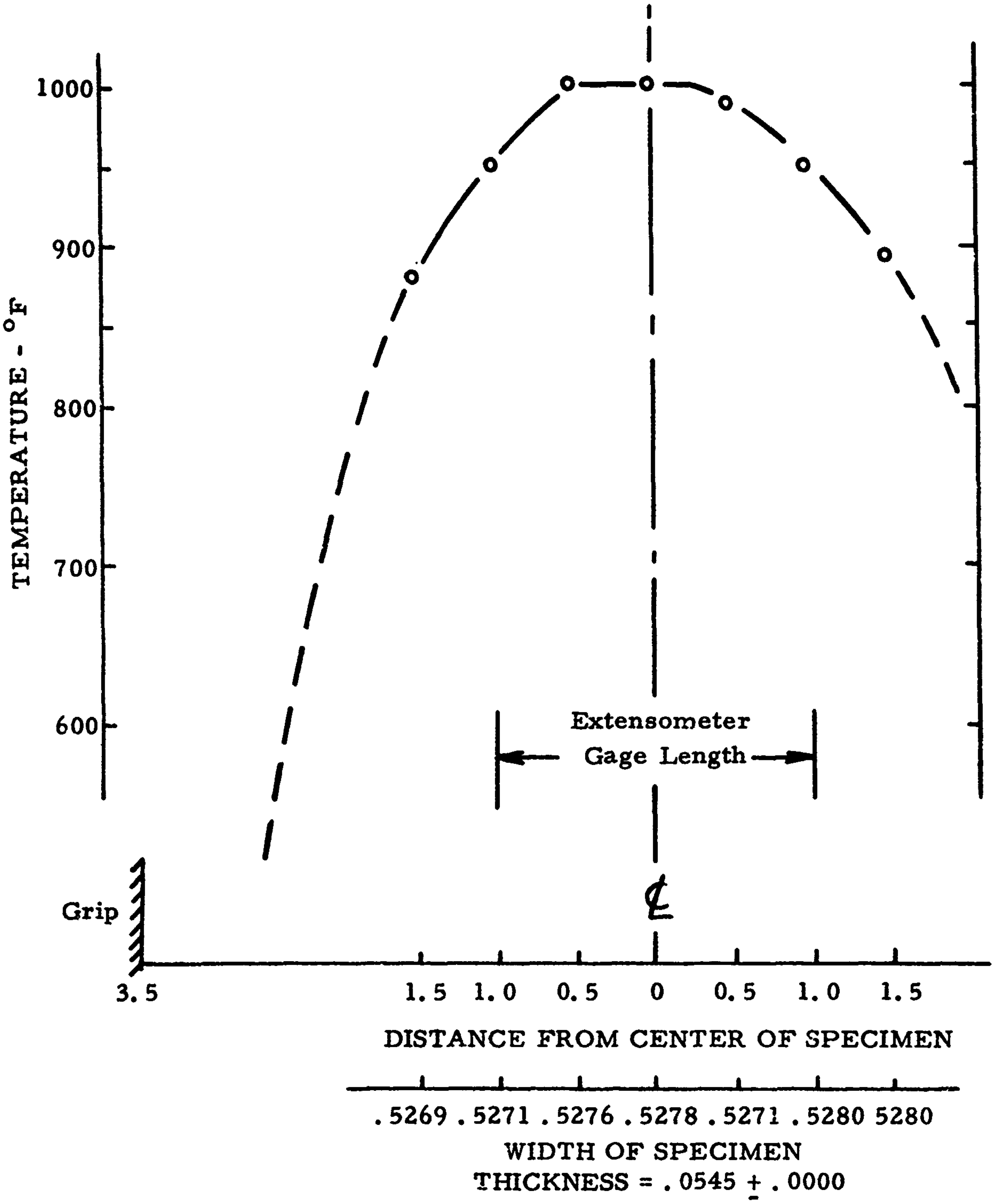


Figure 40. Temperature Distribution in a Resistance Heated Tungsten Strip Specimen at 1000°F

TABLE L

SPECIMEN NUMBERING SYSTEM

For Tungsten Procured to HMS 6-1066 from Five Producers.

D B - 10

10 — **Specimen number. Two sheets for each powder lot. Specimens numbered 1 through 6 from one sheet and 7 through 12 from the other.**

B — **Powder lot code. Three powder lots from each producer except Producer C.**

D — **Producer Code**

TABLE LI

TENSILE TEST RESULTS - PRODUCER A

Specimen	Temperature (°F)	UTS (KSI)	0.2% YS (KSI)	Elastic Modulus (PSI x 10^6)	Elongation (%) (1)	Reduction Area (%) (2)
AA-6	RT	198.4 (d)	--	50	.08	--
AA-12	RT	215.7 (d)	--	47	.13	--
AB-6	RT	198.0 (d)	--	46	0	--
AB-12	RT	107.5	--	47	0	--
AC-6	RT	145.0 (d)	--	45	0	--
AC-12	RT	177.5 (d)	--	46	0	--
Average	RT	173.7	--	47	.03	--
AA-1	1000	124.5	115.5	45	2.8	24
AA-10	1000	123.1	112.0	49	3.1	25
AB-2	1000	115.8	105.3	41	3.6	40
AB-7	1000	108.0	98.8	43	3.7	40
AC-5	1000	126.5	114.8	41	3.9	34
AC-10	1000	124.0	112.9	42	3.3	40
Average	1000	120.3	109.9	43	3.4	34
AA-3	2000	81.0	67.2	34	5.0	99 (c)
AA-9	2000	82.1	68.1	34	5.0	99 (c)
AB-5	2000	75.8	61.9	34	4.2	99 (c)
AB-9	2000	76.7	66.4	29	5.8	99 (c)
AC-3	2000	86.2	70.7	36	4.9	99 (c)
AC-8	2000	83.9	69.2	36	4.1	99 (c)
Average	2000	80.9	67.2	34	4.8	99
AA-4	3600	9.00	4.42	--	38	50
AA-8	3600	8.93	4.52	--	30	(i)
AB-1	3600	8.55	--	--	34	(i)
AB-8	3600	8.79	3.92	--	39	44
AC-4	3600	9.00	4.56	--	32	(i)
AC-7	3600	9.61	4.25	--	26	(i)
Average	3600	8.98	4.33	--	33	47
AA-2	4400	3.80	2.10	--	25	31
AA-7	4400	4.07	2.22	--	18	31
AB-3	4400	3.95	2.22	--	23	(i)
AB-11	4400	4.35	2.36	--	20	(i)
AC-2	4400	4.26	2.36	--	20	37
AC-11	4400	4.02	2.07	--	26	(i)
Average	4400	4.07	2.22	--	22	33

See Table LIV for Notes

TABLE LII

TENSILE TEST RESULTS - PRODUCER B

Specimen	Temperature (°F)	UTS (KSI)	0.2% YS (KSI)	Elastic Modulus (PSI x 10^6)	Elongation (%) (1)	Reduction Area (%) (2)
BA-2	RT	224.0 (g)	--	54	.11	--
BA-12	RT	239.1 (d)	235.5	54	.33	--
BB-2	RT	232.6	225.6	49	.74	--
BB-12	RT	231.4 (d)	226.1	53	1.52	--
BC-6	RT	227.7 (d)	225.3	50	.31	--
BC-12	RT	240.8 (d)	--	55	.16	--
Average	RT	232.6	228.1	52	.53	--
BA-4	1000	137.5	123.0	47	3.8	44
BA-11	1000	131.2	124.1	52	2.3	23
BB-1	1000	136.3 (h)	122.5	43	2.4	25
BB-7	1000	134.4 (h)	116.6	46	2.0	14
BC-2	1000	143.5	124.8	48	3.0	34
BC-7	1000	142.6 (h)	119.7	49	3.3	32
Average	1000	137.6	121.8	47	2.8	27
BA-3	2000	89.5	73.9	36	5.8	99 (c)
BA-10	2000	89.6	75.1	--	5.3	99 (c)
BB-3	2000	96.2	80.1	34	3.9	99 (c)
BB-9	2000	93.8	77.5	36	4.6	99 (c)
BC-1	2000	96.3	78.0	38	4.6	99 (c)
BC-10	2000	97.6	80.9	33	4.8	99 (c)
Average	2000	93.8	77.1	35	4.8	99
BA-1	3600	9.62	6.12	17	18	34
BA-9	3600	9.47	5.83	13	18	37
BB-4	3600	10.27	6.43	16	20	29
BB-8	3600	10.28	6.50	--	22	25
BC-3	3600	10.90	6.70	--	23	30
BC-11	3600	10.20	6.60	--	18	29
Average	3600	10.12	6.36	15	22	31
BA-5	4400	4.94	3.55	--	11	22
BA-8	4400	4.65	3.23	--	10	23
BB-5	4400	4.81	3.33	--	12	24
BB-10	4400	4.63	3.36	--	11	23
BC-4	4400	4.88	3.46	--	11	22
BC-8	4400	4.68	3.25	--	12	22
Average	4400	4.76	3.36	--	11	23

See Table LIV for Notes.

TABLE LIII

TENSILE TEST RESULTS - PRODUCER C

Specimen	Temperature (^oF)	UTS (KSI)	0.2% YS (KSI)	Elastic Modulus (PSI x 10^6)	Elongation (%) (a)	Reduction Area (%) (a)
CA-4	RT	196.8	--	51	.11	--
CA-9	RT	125.1 (d)	--	--	0	--
CB-2	RT	110.7 (d)	--	50	0	--
CB-11	RT	118.0	--	48	0	--
Average	RT	137.6	--	50	.03	--
CA-3	1000	109.4	103.1	38	2.6	43
CA-8	1000	108.3	99.0	39	3.1	45
CB-10	1000	108.0	97.8	47	3.3	44
CB-4	1000	108.3	99.8	42	2.5	41
Average	1000	108.5	99.9	42	2.9	43
CA-2	2000	76.6	64.8	35	4.5	71
CA-10	2000	75.5	61.7	38	3.8	67
CB-3	2000	78.5	70.2	38	3.9	55
CB-8	2000	78.1	68.9	38	4.1	60
Average	2000	77.1	66.4	37	4.1	64
CA-1	3600	9.19	5.14	~30	17	21
CA-11	3600	9.52	5.58	~29	17	21
CB-1	3600	8.57	4.50	~21	>17	--
CB-7	3600	9.16	4.90	~22	23	25
Average	3600	9.11	5.03	~26	19	22
CA-6	4400	4.30	3.20	--	10	17
CA-7	4400	4.06	3.01	~20	11	17
CB-5	4400	3.86	2.73	~19	12	20
CB-9	4400	3.82	2.67	~16	12	22
Average	4400	4.01	2.90	~18	11	19

See Table LIV for Notes

TABLE LIV

TENSILE TEST RESULTS - PRODUCER E

Specimen	Temperature (°F)	UTS (KSI)	0.2% YS (KSI)	Elastic Modulus (PSI x 10^6)	Elongation (%) (a)	Reduction of Area (%) (b)
EA-8	RT	19.3	--	--	0	--
EB-2	RT	13.2	--	--	0	--
EC-2	RT	73.1	--	63	[illegible]	--
EC-11	RT	16.6	--	--	[illegible]	--
EC-3	1000	57.9 (e)	--	48	--	--
EC-10	1000	95.6	89.4	41	2.3	20
EC-5	2000	65.1	56.0	35	3.3	99 (c)
EC-9	2000	64.3	58.5	44	3.3	99 (c)
Average	2000	64.7	57.2	39	3.3	99
EA-11	3600	10.84	5.90	--	18	24
EB-3	3600	10.37	5.75	--	--	24
EC-4	3600	10.12	5.90	~23	19	30
EC-8	3600	10.24	5.59	~25	19	25
Average	3600	10.39	5.78	~24	19	26
EA-7	4400	4.98 (f)	3.58	~18	5.3	10
EA-10	4400	5.31 (f)	3.78	--	8.8	9
EB-1	4400	5.43	3.90	~18	6.8	13
EC-1	4400	5.14 (f)	3.56	--	7.4	13
EC-7	4400	5.59 (f)	3.94	~16	7.8	9
Average	4400	5.29	3.75	~17	7.2	11

Notes for Tables LI, LII, LIII, LIV, and LV

(a) RT elongation values are plastic portion only. Elevated temperature values are elastic plus plastic.

(b) Fracture area is often difficult to define so RA values are approximate.

(c) Specimen necked to sharp edge.

(d) Failed outside of gage length, but not in grip.

(e) Failed outside of gage length where the temperature is significantly below the test temperature.

(f) Failed at extensometer point.

(g) Failed in grip.

(h) Failed at thermocouple spotweld.

(i) Fracture surface cannot be defined.

TABLE LV

TENSILE TEST RESULTS - PRODUCER F

Specimen	Temperature (^oF)	UTS (KSI)	0.2% YS (KSI)	Elastic Modulus (PSI x 10^6)	Elongation (%) (a)	Reduction of Area (%) (b)
FA-6	RT	154.0	--	52	0	--
FA-12	RT	130.0	--	47	0	--
FB-6	RT	146.0	--	51	0	--
FB-12	RT	168.0	--	51	0	--
FC-5	RT	211.9	--	49	.08	--
FC-6	RT	208.7	--	50	.15	--
FC-11	RT	137.1	--	50	0	--
Average	RT	165.1	--	50	.03	--
FA-5	1000	108.0	98.0	44	3.3	56
FA-8	1000	104.6	97.5	42	3.5	52
FB-2	1000	110.5	102.5	46	3.1	51
FB-11	1000	106.0	100.0	40	3.1	50
FC-1	1000	109.0	100.2	44	2.9	36
FC-8	1000	112.2	106.0	40	3.0	45
Average	1000	108.4	100.7	43	3.1	48
FA-1	2000	76.1	67.1	32	4.8	99 (c)
FA-11	2000	73.1	64.4	36	4.6	99 (c)
FB-1	2000	79.5	69.9	33	5.3	99 (c)
FB-7	2000	76.2	66.5	35	5.3	99 (c)
FC-2	2000	80.6	68.0	35	4.5	99 (c)
FC-9	2000	80.0	67.8	34	4.8	99 (c)
Average	2000	77.6	67.3	34	4.9	99
FA-3	3600	9.70	5.70	--	28	34
FA-7	3600	9.82	5.45	~20	29	32
FB-3	3600	10.09	5.67	~20	28	34
FB-9	3600	9.82	5.71	--	28	33
FC-3	3600	9.92	5.47	~20	29	35
FC-10	3600	9.76	5.30	~21	28	37
Average	3600	9.85	5.55	~20	28	34
FA-4	4400	4.28	2.88	--	--	--
FA-10	4400	4.04	2.58	~10	14	24
FB-4	4400	3.99	2.49	--	15	23
FB-10	4400	3.86	2.50	--	16	23
FC-4	4400	3.64	2.23	--	14	23
FC-7	4400	3.46	2.11	~10	15	25
Average	4400	3.88	2.46	~10	15	24

See Table LIV for Notes

TABLE LVI

AVERAGE TENSILE TEST RESULTS FOR TUNGSTEN SHEET PER HMS 6-1066

Producer	Temperature (°F)	UTS (KSI)	0.2% YS (KSI)	Elastic Modulus (PSI x 10^6)	Elongation (%) (a)	Reduction of Area (%) (b)
A	RT	173.7	--	47	.03	--
B	RT	232.6	228.1	52	.53	--
C	RT	137.6	--	50	.03	--
E	RT	Below 73.1	--	--	0	--
F	RT	165.1	--	50	.03	--
A	1000	120.3	109.9	43	3.4	34
B	1000	137.6	121.8	47	2.8	27
C	1000	108.5	99.9	42	2.9	43
E	1000	95.6	89.4	44	2.3	20
F	1000	108.4	100.7	43	3.1	48
A	2000	80.9	67.2	34	4.8	99
B	2000	93.8	77.1	35	4.8	99
C	2000	77.1	66.4	37	4.1	64
E	2000	64.7	57.2	39	3.3	99
F	2000	77.6	67.3	34	4.9	99
A	3600	8.98	4.33	--	33	47
B	3600	10.12	6.36	~15	22	31
C	3600	9.11	5.03	~26	19	22
E	3600	10.39	5.78	~24	19	26
F	3600	9.85	5.55	~20	28	34
A	4400	4.07	2.22	--	22	33
B	4400	4.76	3.36	--	11	23
C	4400	4.01	2.90	~18	11	19
E	4400	5.29	3.75	~17	7.2	11
F	4400	3.88	2.46	~10	15	24

Notes:

(a) RT elongation values are plastic portion only. Elevated temperature values are elastic plus plastic.

(b) Fracture area is often difficult to define so RA values are approximate.

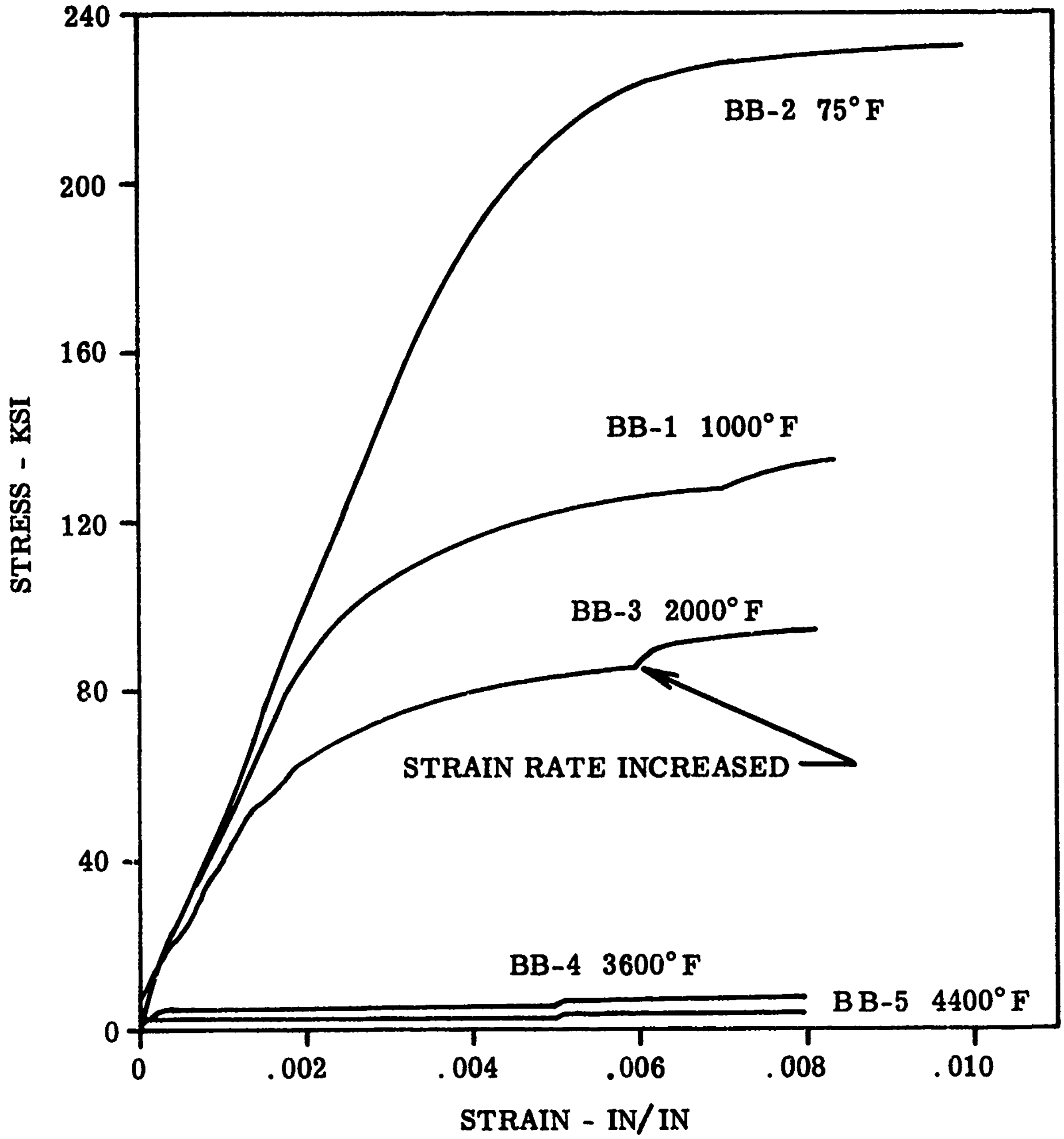


FIGURE 41. STRESS-STRAIN CURVES FOR TUNGSTEN SHEET

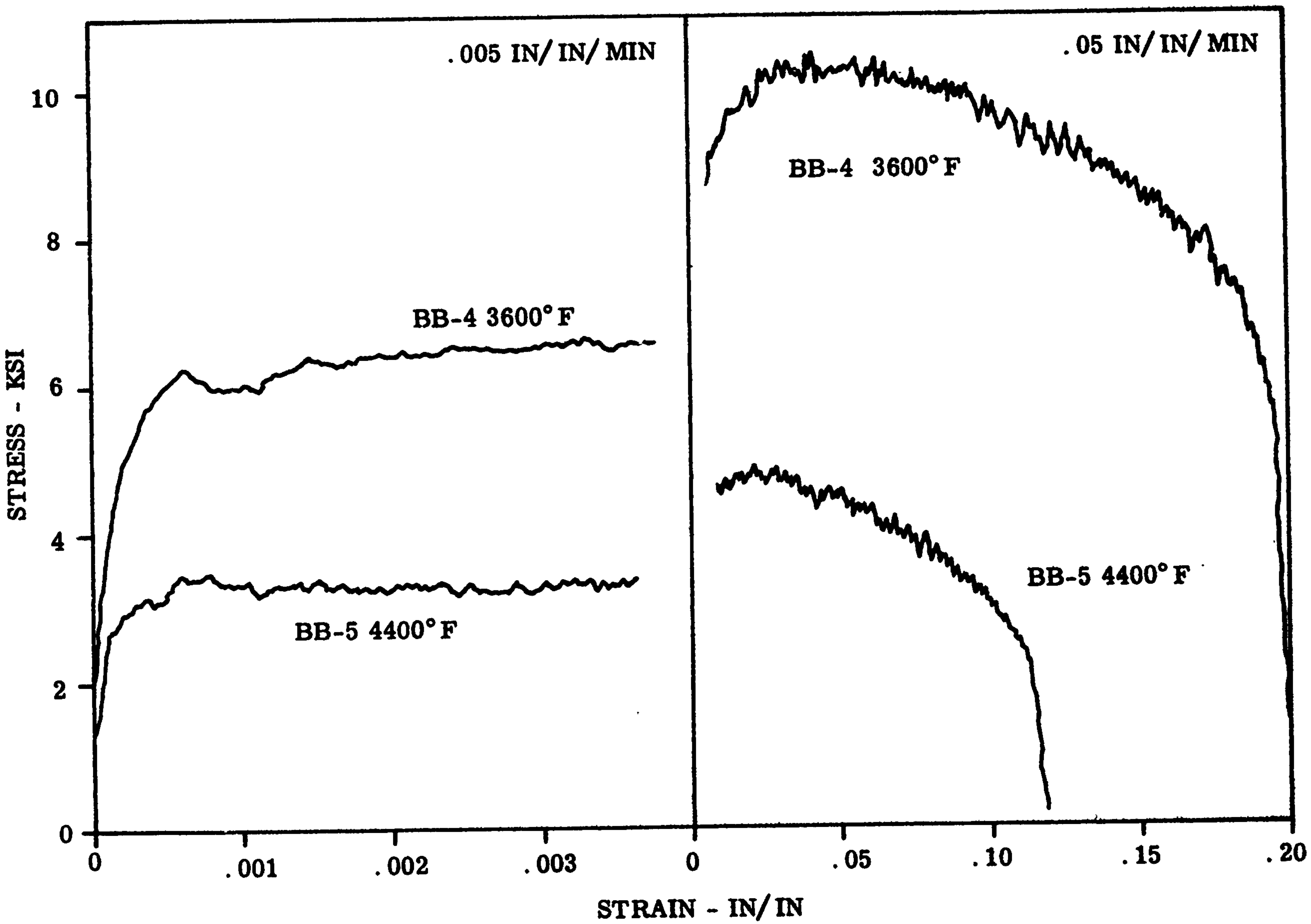


FIGURE 42. FULL STRESS-STRAIN CURVES FOR PRODUCER B TUNGSTEN AT 3600° AND 4400° F

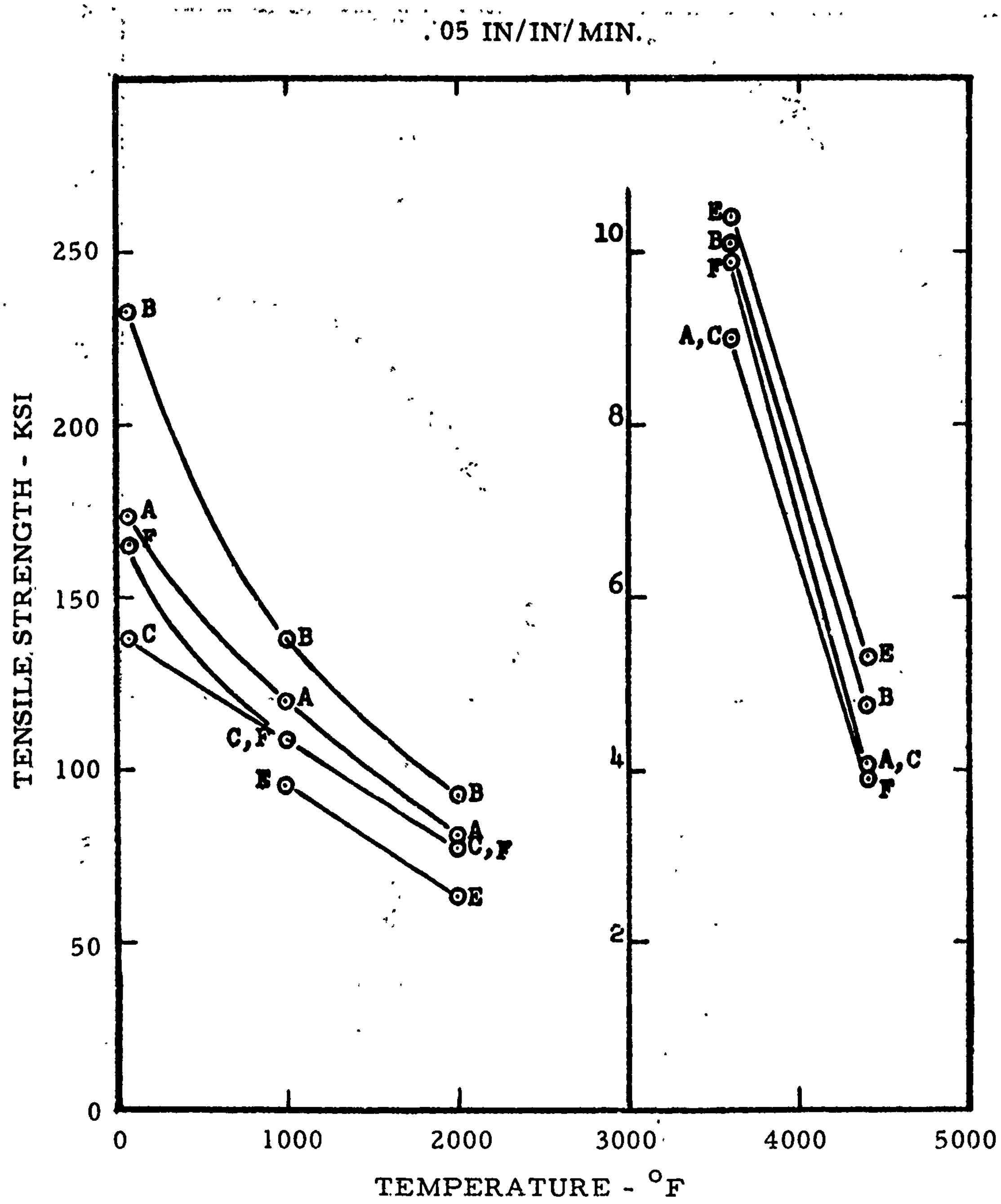


Figure 43. Average Tensile Strength vs. Temperature for Tungsten Sheet from Five Producers

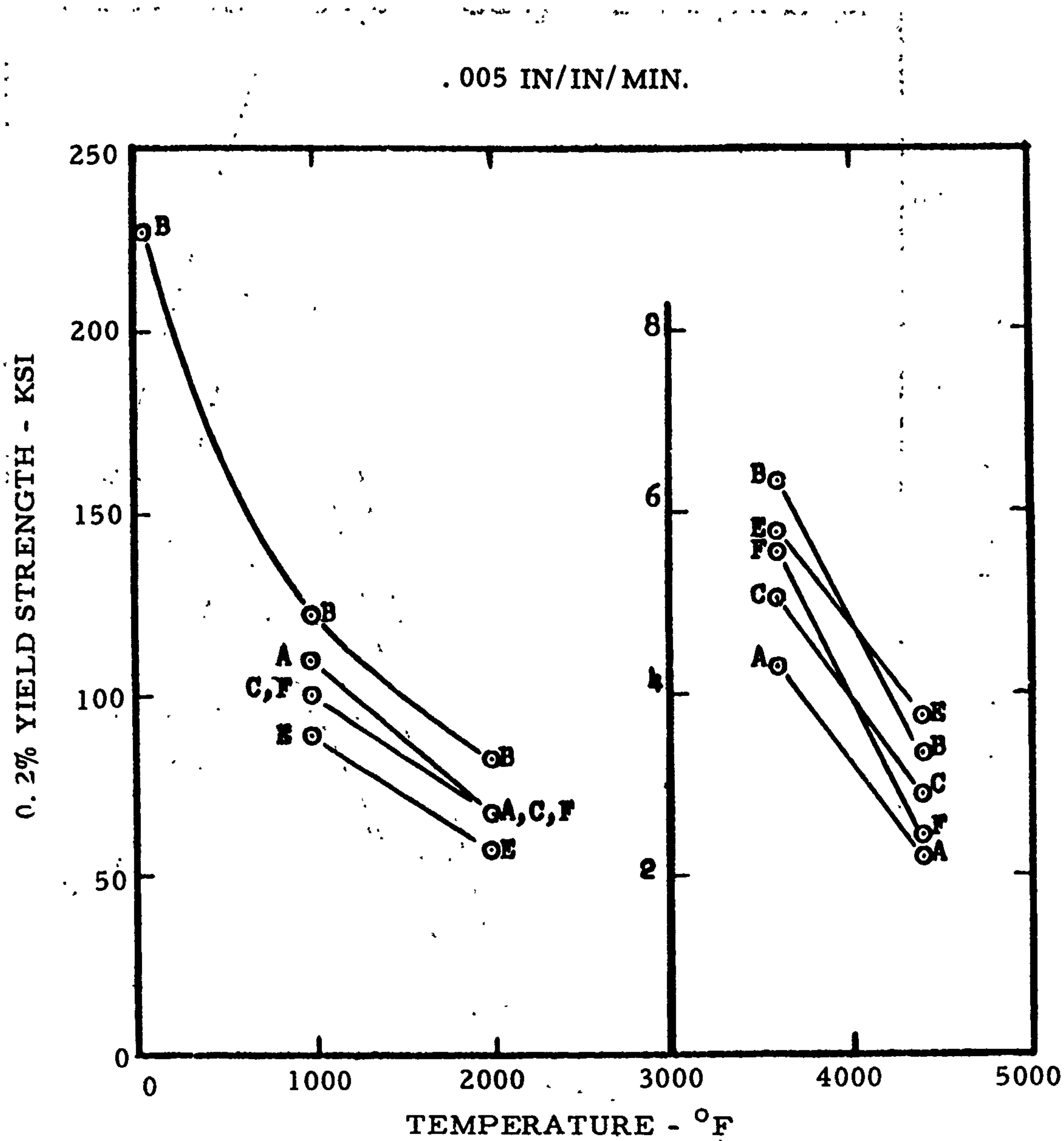


Figure 44. Average 0.2% Yield Stress vs. Temperature for Tungsten Sheet from Five Producers

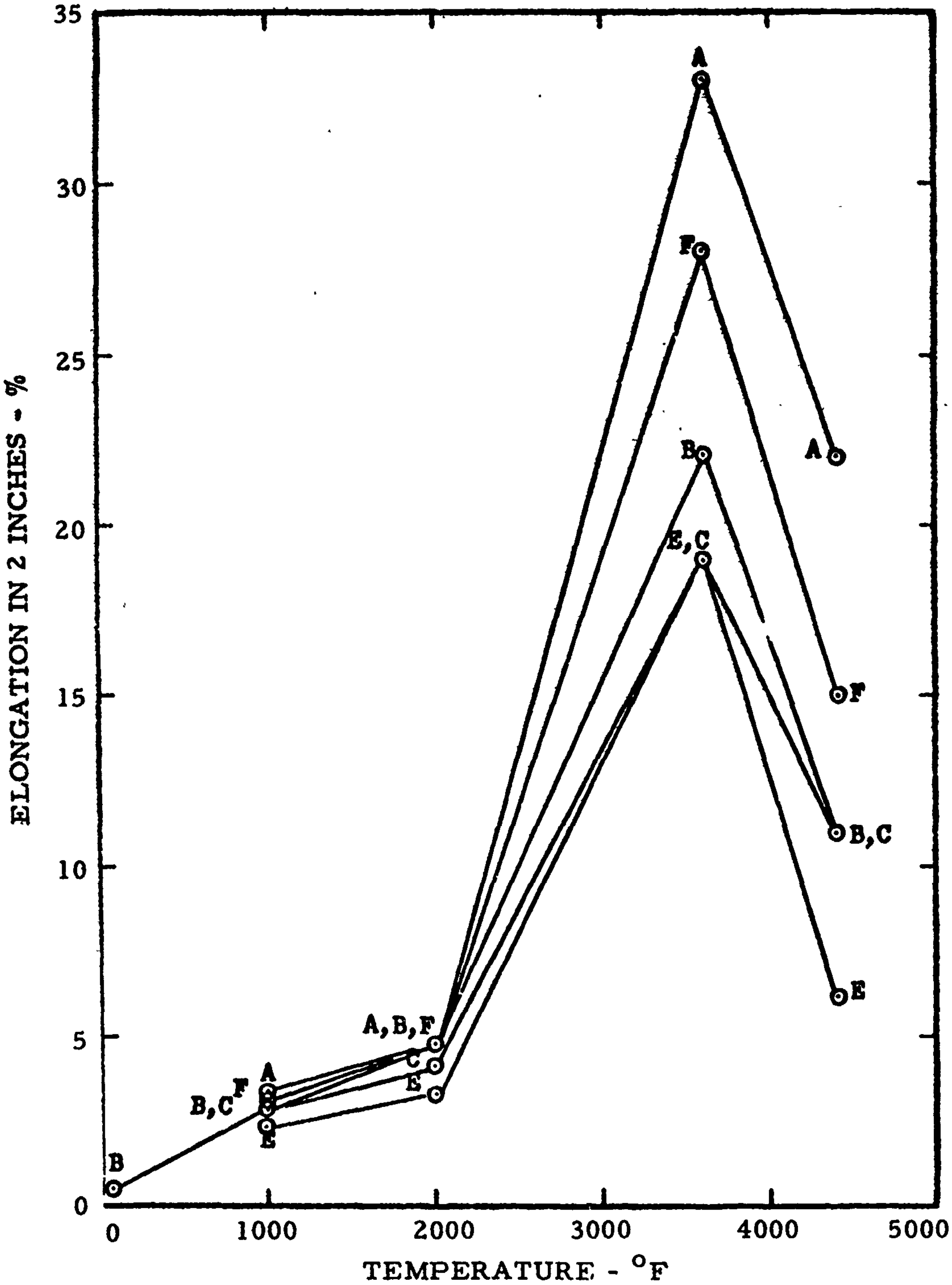


Figure 45. Average Elongation vs. Temperature for Tungsten Sheet from Five Producers

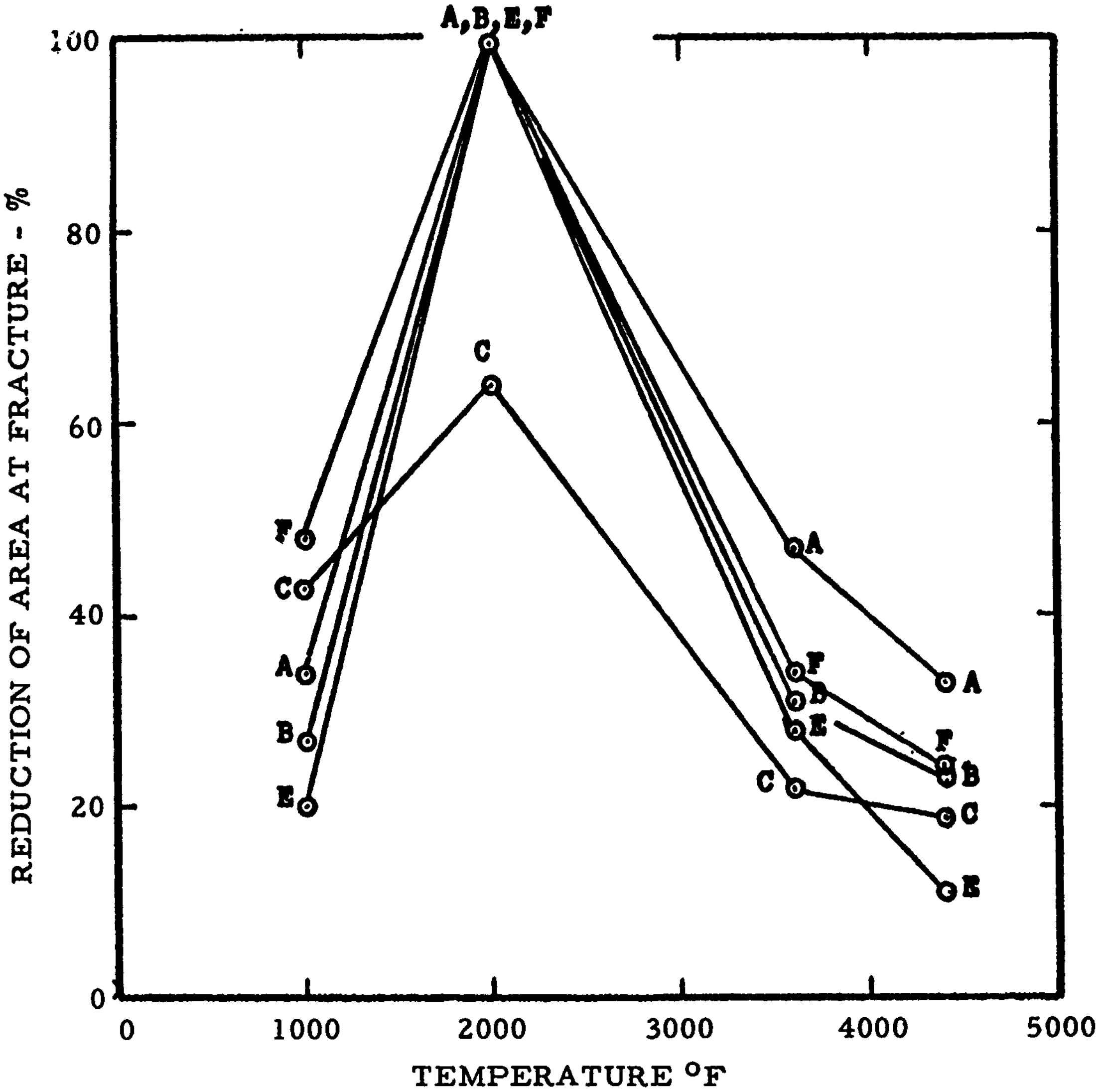


Figure 46. Average Reduction of Area vs. Temperature for Tungsten Sheet from Five Producers

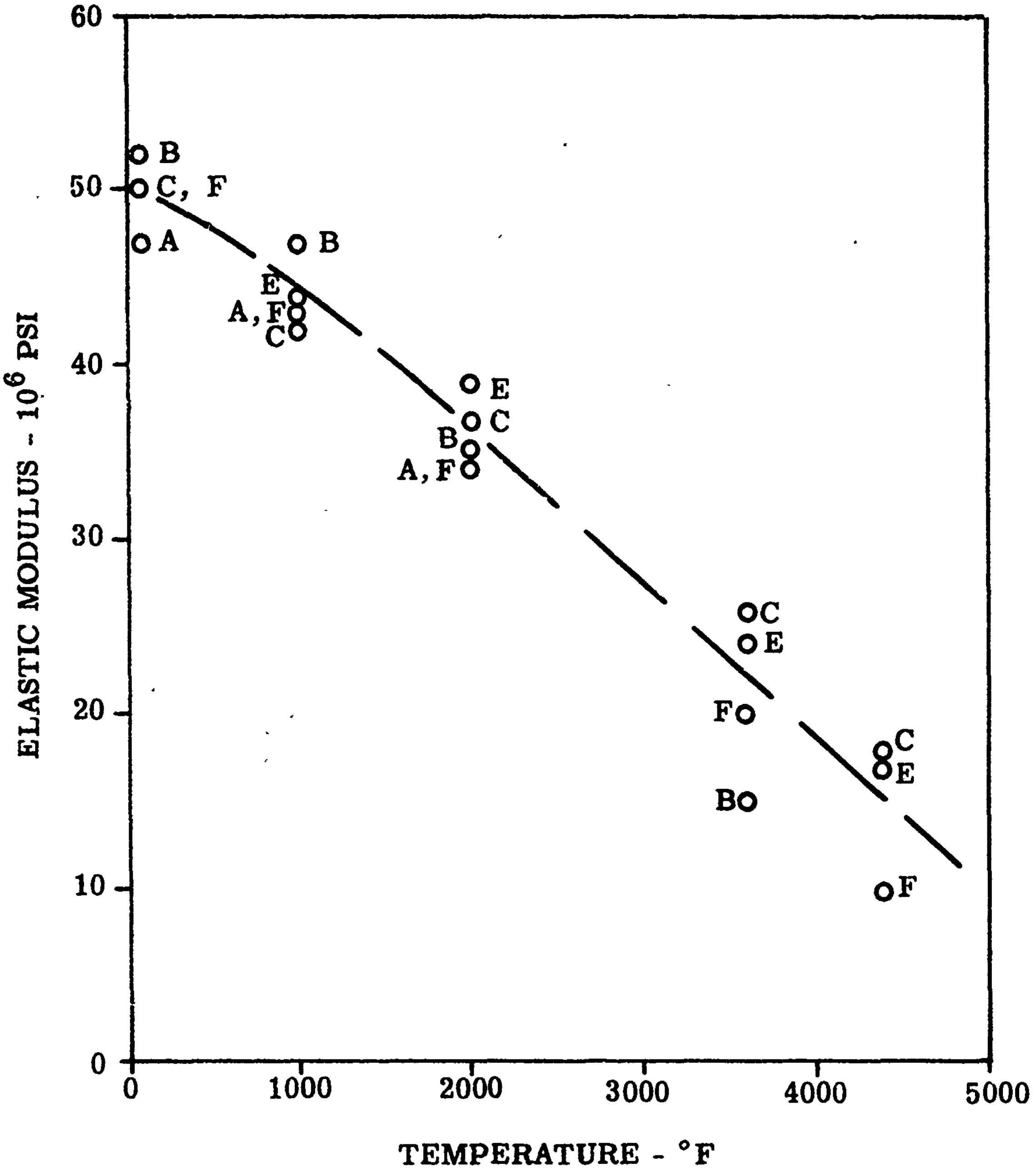


FIGURE 47 AVERAGE ELASTIC MODULUS vs. TEMPERATURE FOR TUNGSTEN SHEET

TABLE LVII

ELASTIC MODULUS OF TUNGSTEN SHEET AT ROOM TEMPERATURE

Strain determined with roorr temperature extensometer.

		Elastic Modulus - 10^6 PSI				
	Loading Number	AIC-9	AC-1	BA-1	CA-5	FB-5
1.	Secondary Modulus	51.3	51.1	49.5	47.4	--
1.	Primary Modulus	53.8	54.7	56.2	56.1	50.2
2.		54.3	56.2	57.5	52.2	51.5
3.		54.3	57.0	57.5	52.3	55.0
4.		--	57.0	58.2	52.4	55.7
5.		--	--	--	--	55.7

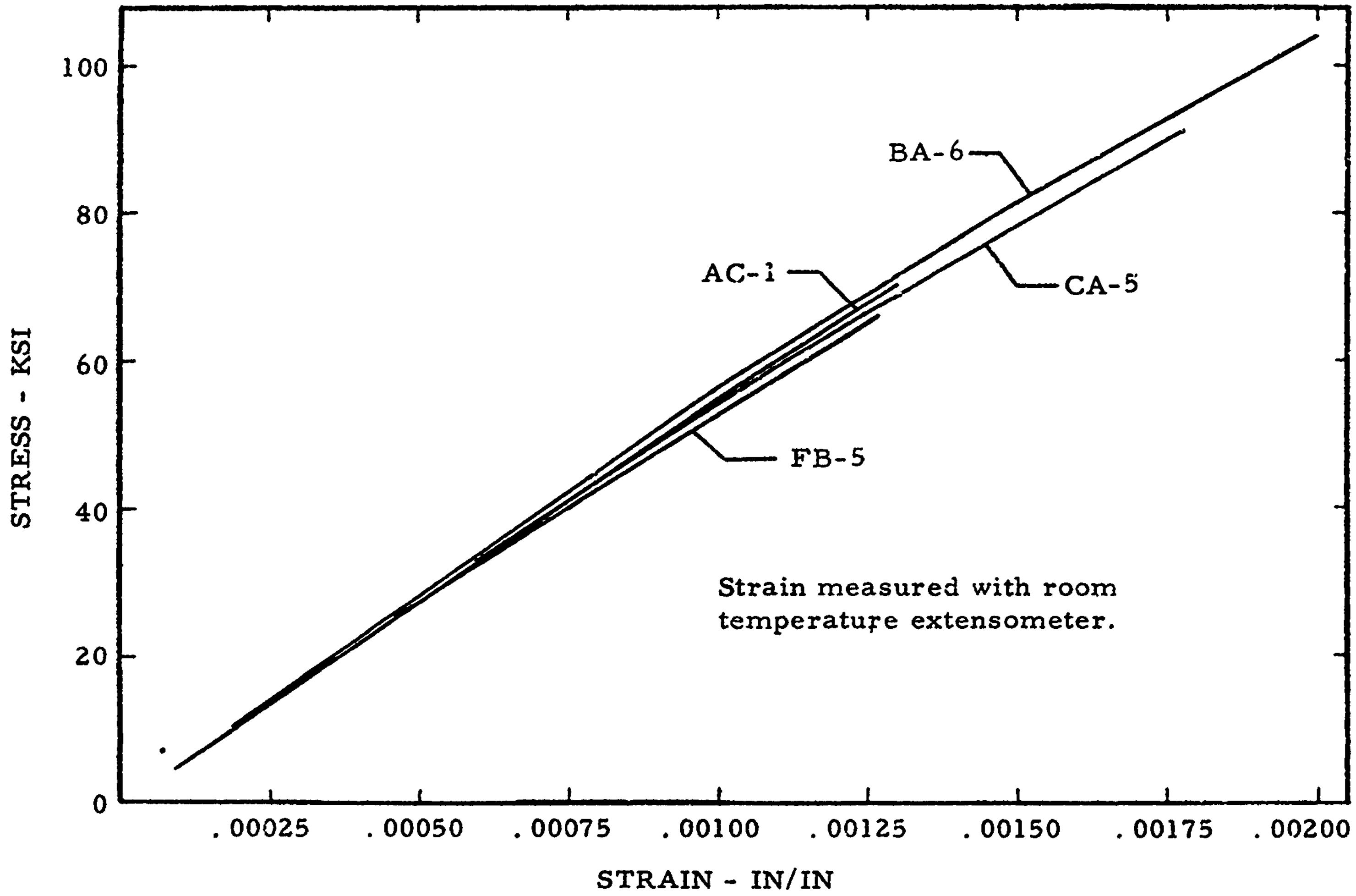


Figure 48. Room Temperature Stress-Strain Curves for Tungsten Sheet

TABLE LVIII

ROCKWELL SUPERFICIAL HARDNESS OF .050" TUNGSTEN SHEET

Readings were taken in center of each sheet before fabrication into specimens.

Specimen No.	Hardness Values Rockwell 45-N					Ave.
AA-3	51.0	52.4	49.6	50.9	50.2	50.8
AA-9	52.1	52.3	51.4	50.3	51.0	51.4
AB-3	50.8	51.5	52.9	51.3	51.7	51.6
AB-9	51.2	46.7	48.2	49.3	54.3	49.9
AC-3	50.4	48.3	52.0	52.1	49.8	50.5
AC-9	50.4	49.9	50.0	49.0	53.0	50.5
BA-3	52.8	52.7	51.1	51.2	53.9	52.3
BA-9	56.1	52.3	51.5	53.6	51.6	53.0
BB-3	51.0	51.9	51.1	52.8	52.8	51.9
BB-9	51.8	53.0	50.1	53.2	53.6	52.3
BC-3	53.1	53.4	52.4	54.0	53.8	53.3
BC-9	53.1	53.0	51.0	52.1	54.5	52.7
CA-3	51.3	51.0	50.9	51.1	51.0	51.1
CA-9	49.5	50.6	49.6	50.1	51.3	50.2
CB-3	49.7	50.3	50.0	50.6	50.5	50.2
CB-9	50.6	51.0	49.4	49.8	50.3	50.1
EA-3	46.0	45.8	47.8	50.0	48.2	47.6
EA-9	47.2	46.8	48.2	49.0	48.7	48.0
EB-3	50.0	49.5	46.8	49.9	45.5	48.3
EB-9	46.9	47.0	51.0	49.1	46.5	48.1
EC-3	45.9	49.2	49.2	49.7	50.2	48.8
EC-9	49.0	48.3	48.5	50.8	47.0	48.7
FA-3	50.3	50.1	50.0	49.5	49.4	50.0
FA-9	50.2	51.2	49.3	49.2	48.8	49.9
FB-3	49.2	50.6	50.3	50.4	51.5	50.4
FB-9	48.7	48.9	49.0	50.9	49.3	49.4
FC-3	51.3	51.6	50.0	50.7	50.8	50.9
FC-9	50.3	50.6	50.6	51.7	49.6	50.6

TABLE LIX

AVERAGE TENSILE STRENGTH AND AVERAGE HARDNESS FOR .050" TUNGSTEN SHEET

	Producer	UTS at R. T. (KSI)	Hardness Rockwell 45-N
Test Results From Part II	A	153.3	50.2
	B	29.0	45.1
	C	90.8	48.4
Producer Survey Material per HMS 6-1066	A	173.7	50.8
	B	232.6	52.6
	C	137.6	50.4
	E	13 to 73	48.2
	F	165.1	50.2

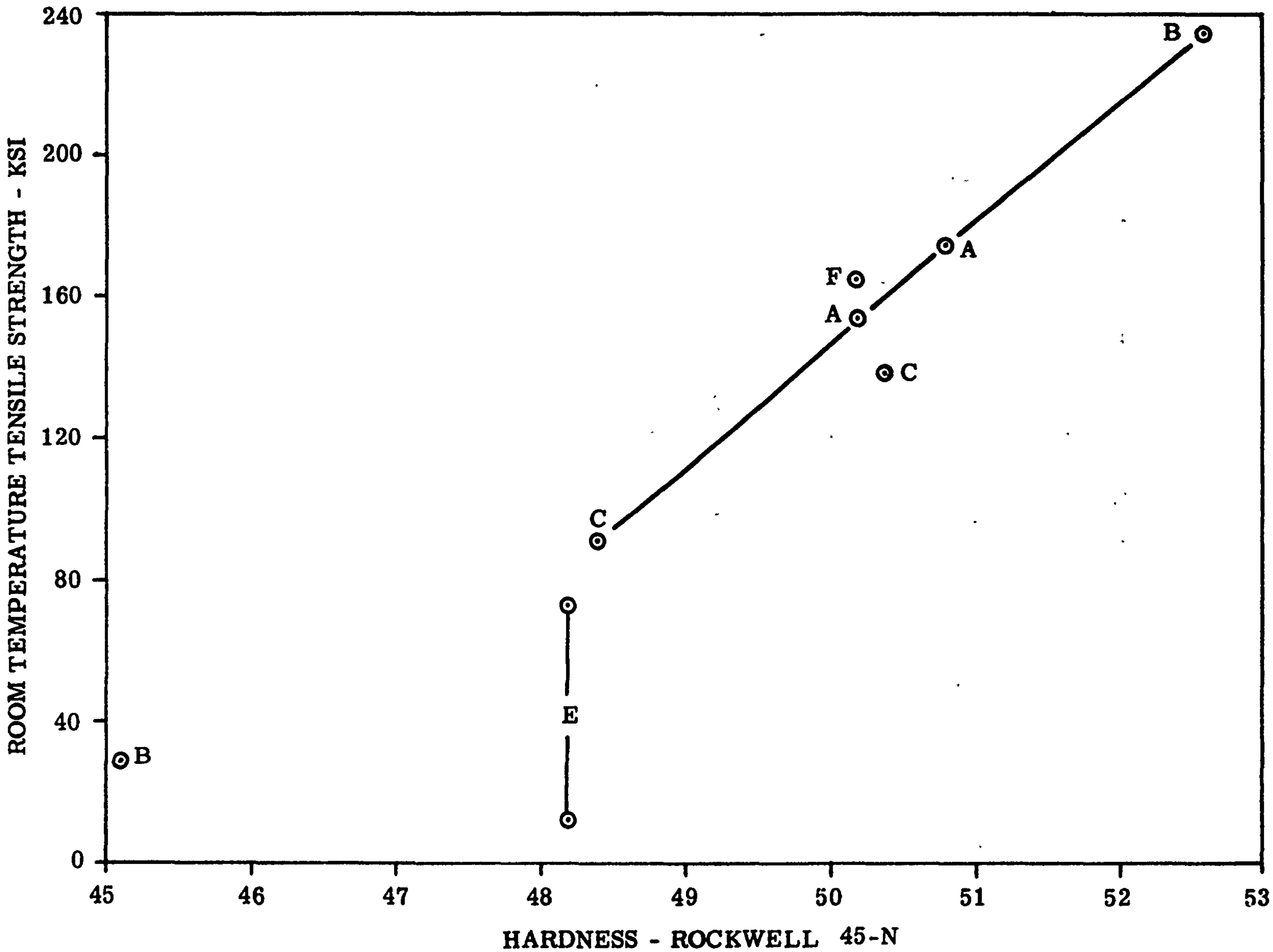


FIGURE 49 HARDNESS vs. TENSILE STRENGTH FOR TUNGSTEN

TABLE LX

CHEMICAL AND SPECTROGRAPHIC ANALYSES

Composition, PPM by weight

Specimen	O_2 (a)	H_2 (a)	N_2 (b)	C (c)	Mo (d)	Fe (d)	Zr (d)	Zn (d)
AA-6	25	1	3	12	20-200	P-100	P-10	P-100
AB-6	39	P-1	6	12	20-200	P-100	P-10	P-100
AC-6	30	P-1	15	12	20-200	P-100	P-10	P-100
BA-2	23	1	9	30	P-10	P-100	P-10	ND
BB-1	13	2	3	10	P-10	P-100	P-10	ND
BC-6	61	2	16	10	P-10	P-100	P-10	ND
CA-5	37	P-1	8	25	10-100	P-100	P-10	P-100
CB-6	21	2	2	36	10-100	P-100	P-10	P-100
FA-3	7	P-1	13	15	10-100	P-100	P-10	P-100
FB-12	13	P-1	6	11	10-100	P-100	P-10	P-100
FC-12	20	P-1	20	11	10-100	P-100	P-10	P-100
EB-1	8	P-1	6	11	10-100	P-100	P-10	P-100
EC-1	7	P-1	2	28	10-100	P-100	P-10	P-100

P = Present but less than amount indicated
ND = Not detected
(a) = Vacuum fusion analysis
(b) = Micro-Kjeldahl analysis
(c) = Conductometric analysis
(d) = Semi-quantitative spectrographic analysis

TABLE LXI

SEMI-QUANTITATIVE SPECTROGRAPHIC ANALYSES FOR ALL SPECIMENS SHOWN IN TABLE LX

P = Present but less than amount indicated
ND = Not detected

Element	PPM by Weight
Si	P-100
Al	P-100
Ti	P-10
Cu	P-10
Ni	P-10
Cr	P-100
V	P-100
Mn	P-10
Ca	P-100
Mg	P-10
Bi	P-100
Pb	P-50
Sn	P-100
Ag	ND
Co	P-10
Sb	ND
As	ND
B	ND
Na	P-100
Li	P-100
Cd	ND

PRODUCER B

R45-N 53.0 UTS 239.1 KSI

PRODUCER F

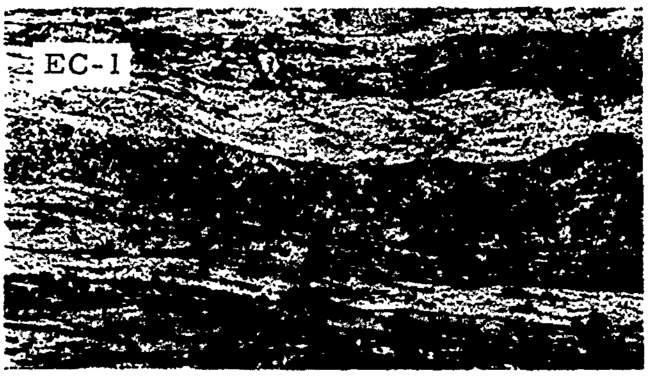
R45-N 50.9 UTS 208.7 KSI

PRODUCER A

R45-N 50.8 UTS 198.4 KSI

PRODUCER C

R45-N 50.1 UTS 118.0 KSI

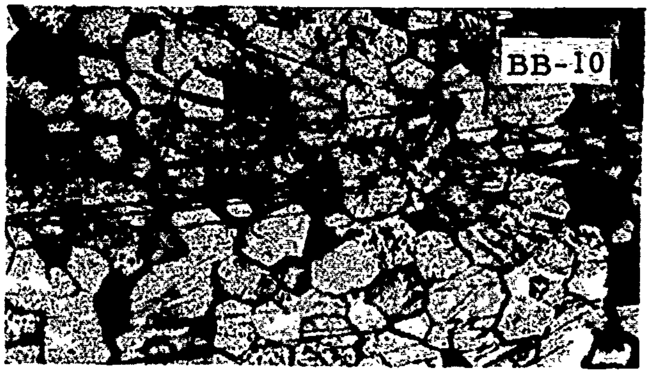


PRODUCER E

R45-N 48.8 UTS 73.1 KSI

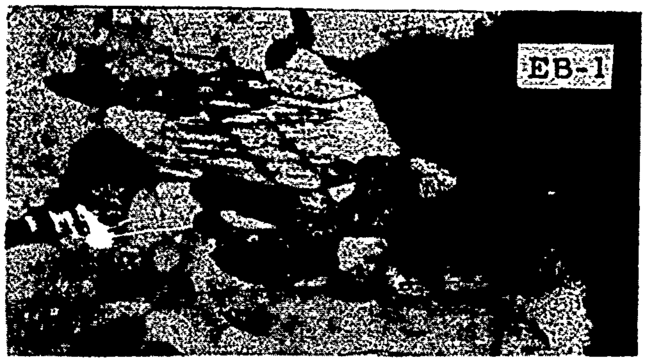
Figure 50. Microstructure of As-Received Tungsten from Five Producers. Room Temperature Tensile Strength and Hardness of Corresponding Sheet Noted. Longitudinal Section. 200 X

PRODUCER A



PRODUCER B

PRODUCER C



PRODUCER E

PRODUCER F

Figure 51. Microstructure of Tungsten at Fracture Zone After Testing at 4400°F Longitudinal Section. 200 X

APPENDIX

TUNGSTEN SHEET SPECIFICATION

HMS 6-1066

	MATERIAL SPECIFICATION	NUMBER HMS 6-1066 ISSUED 5-4-61 REVISED 7-13-61

TITLE: COMMERCIALLY PURE TUNGSTEN SHEET

1. Acknowledgement. A vendor shall mention this specification in all quotations and when acknowledging purchase orders.

2. Form. .050 inch thick sheet, rolled from ingots which are pressed from powder and consolidated by sintering.

3. Application. For parts requiring exposure at high temperatures.

4. Composition.

Tungsten	Major
Molybdenum	0.10% max.
Iron	0.05% max.
Any other single element	0.01% max.

5. Condition

5.1 High degree of cold reduction

5.2 No stress relief heat treatment will be used.

5.3 Matte surface due to acid or caustic cleaning is acceptable.

5.4 Surface roughness as measured with a profilometer shall be less than 200 microinches.

6. Technical Requirements

6.1 Bend Ductility
A minimum of three bend angle test values shall be reported.

Specimen size	-	.050 x .500 x length as required
Stress direction	-	parallel to rolling direction
Bend radius	-	.062 inches
Ram deflection rate	-	0.5 inches/min. (approximate)
Test temperature	-	$350^{o}F$ ($+0^{o}$, -20^{o})
Bend angle	-	80^{o} minimum

6.2 Hardness
A minimum of five test values on Rockwell Superficial Hardness Scale 45-N shall be reported. No single value shall be less than 46.0 and the average shall be 48.0 or greater.

6.3 Microstructure
A highly elongated structure as shown in Figure 52 is desired. The minimum acceptable is shown in Figure 53, and Figure 54 is an example of unacceptable structure.

7. Quality

7.1 Material shall be uniform in quality and condition, clean, sound and free from internal and external imperfections.

7.2 Internal defect area revealed by ultrasonic inspection shall not exceed 1% of the surface area; excluding defects occurring within 1/8 inch of the sheet edge. Edge cracks shall not extend further than 1/8 inch into the sheet.

7.3 Flatness - sheet shall be flat within 1% of the distance between contact points of a straight edge laid in any direction upon the material. The amount of variation shall be determined by measuring the distance from the straight edge to the material at the point of greatest deviation. Figure 55 illustrates the method of measurement.

8. Tolerances

Thickness	± .004 inches
Width	± .060 inches
Length	± .060 inches

9. Identification

Material shall be marked with manufacturer's identification and manufacturer's powder lot number.

10. Rejection

Material not conforming to this specification or to authorized modifications will be subject to rejection.

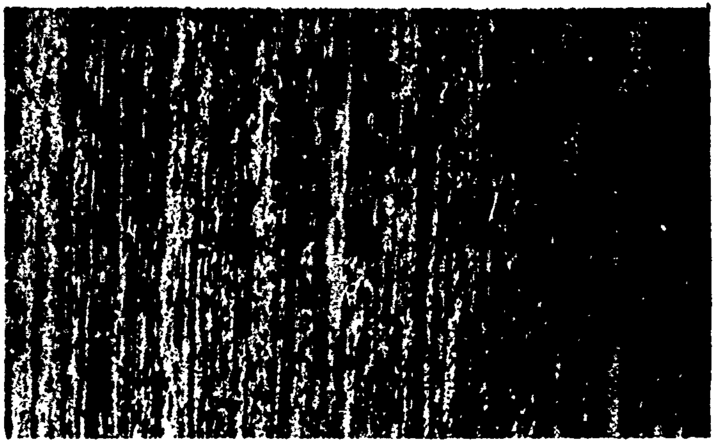
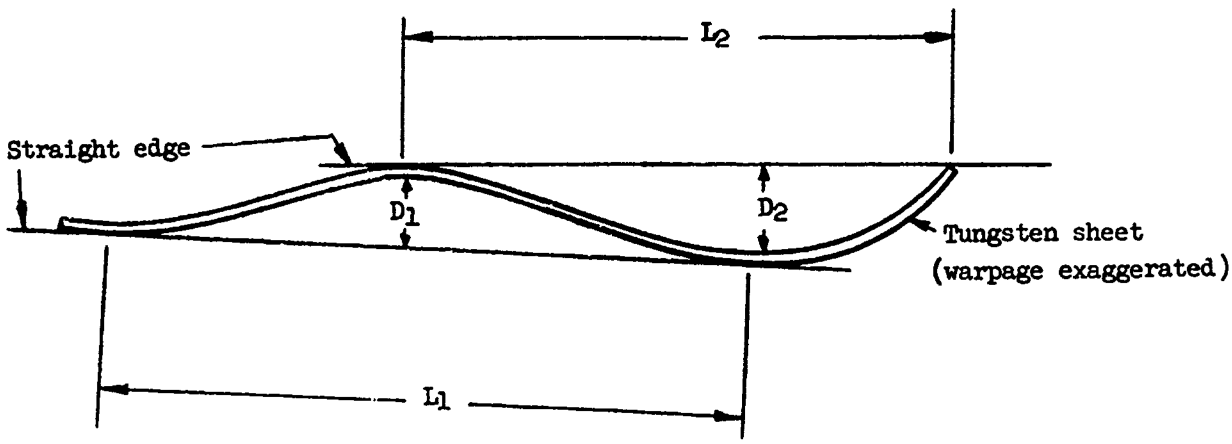


Figure 52. Desired Microstructure. 200 X. Murikami's Etch. Longitudinal Section.

Figure 53. Minimum Acceptable Microstructure. 200 X. Murikami's Etch. Longitudinal Section.

Figure 54. Unacceptable Microstructure. 200 X. Murikami's Etch. Longitudinal Section.



$\frac{D}{L}$ shall not be greater than .01

Figure 55. Measurement of Flatness